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Aero-Propulsive Coupling of an Embedded, Distributed Propulsion System

Michael Kerho

Rolling Hills Research Corporation

NASA Aeronautics Research Mission Directorate (ARMD)

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Outline

- Introduction
- Turboelectric Distributed Propulsion (TeDP)
- Project Scope
- Subscale Test Bed
- Embedded Inlet Design
- CFD Design/Results
  - Design Optimization, Thrust Angle/Level, AOA Effects
  - Differential Thrust Effects
- Wind Tunnel Verification Test
  - Thrust Level, AOA, Differential Thrust Effects
- Conclusions/Next Steps

Introduction

- NASA Subsonic Fixed Wing (SFW) Project N+3 Goals
  - 2025 Timeframe, Based on B777-200LR Baseline
  - Noise: -52dB Reduction
  - Emissions: -80% Reduction
  - **Fuel Burn: -60% Reduction**
- In Order To Meet Goals ⇒ New Configurations, Materials, and Propulsion Technologies
  - Hybrid Blended Wing Body (HBWB) Config.
  - HBWB Provides High Cruise L/D, Noise Shielding
  - With TeDP, HBWB Fuel Burn Reduced 18%-20%**
  - TeDP Uses Electric Motor Driven Fans Coupled Turbine Generators Via Transmission Lines
  - Total Fuel Burn Reduction HBWB+TeDP = 70%-72%**

NX-3 From Felder et. al.

** Assumes Superconducting Motors and Generators

1) Felder et al. ISABE-2011-1340

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TeDP Advantages

- Boundary Layer Ingestion (BLI)
  - Reduces Average Inlet Velocity and Drag of Inlet
  - Reduces Fuel Burn Compared to Pylon Mounted Design
- Reduces Wake Drag of Vehicle
  - Re-energizes Wake of Airframe With Fan Thrust Stream
- Decouples Propulsion From Power
  - Power and Propulsion Can be Placed at Optimum Locations
  - RPM of Power Generating Turbine Independent of Fan RPM
- Very High Effective Bypass Ratio
- Safety: Redundancy For Both Propulsion and Power
- Differential Thrust For Trim and Possible Yaw Control

1) Felder et al. ISABE-2011-1340

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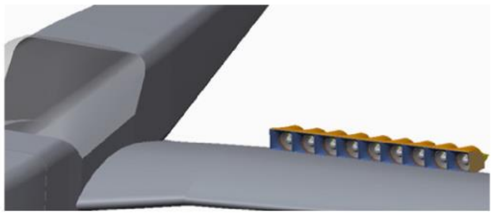
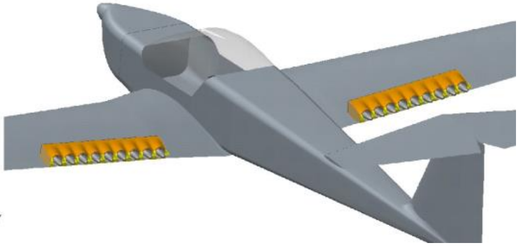
TeDP Challenges

- Inlet Distortion Due to BLI and Inlet Geometry
  - Reduced Fan Performance, Increased Blade Fatigue Due to BLI and Inlet Secondary Flows
- Aerodynamics and Propulsion Closely Coupled
  - Interaction Between Sectional Aero Performance and Thrust Level
  - Changes in Thrust Level Effect:
    - Circulation/Lift , Spillage Induced Blockage, Pitching Moment
- Effect of Individual Fan Thrust Level/Mass Flow on Adjacent Fan Performance and Distortion
- Reliance on Superconducting Motors/Generators to Reduce Propulsion System Weight Fraction
- Increased System Complexity and New Technologies

Current Project

- **LEARN Project: Design Distributed Propulsion System For Small Test Bed Aircraft**
- Develop a Flying Demonstrator For TeDP Concepts, Systems, and Technologies
  - Reduce Development Risk of Larger, Dedicated Configuration
  - Allows Early Investigation of Complex Aero, Propulsion, and Systems
- Phase I Project
  - 3 Fan Half Model
  - CFD and Experimental
- Phase II Project
  - 5 Fan Pseudo 3D Model
  - CFD and Experimental





Subscale Test Bed

- Test Bed Aircraft Allows Early Assessment of Multiple TeDP Technologies and Challenges
  - BLI
    - Distortion Challenges
  - Aerodynamic/Thrust Coupling
    - Effect of Thrust Level and Mass Flow on Sectional Aerodynamic Characteristics (C_l, C_m, Trim and Trim Drag)
    - High Angle-of-Attack Behavior, Stall, Separation and Their Dependence Upon Thrust Level
  - Spanwise Differential Thrust
    - For Trim and Possible Yaw Control
    - Effect of Changing Spanwise Thrust Levels, Mass Flow and Spillage on Neighboring Fan's Thrust and Performance
  - Inlet Area Design
    - Changes in Mass Flow With Thrust Effect Spillage and Blockage
    - Is Moveable Inlet Lip Required to Adjust For Various Flight Conditions?

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Scaling

- Technologies Developed On Test Bed Need To Scale To Full Size Transport Configuration
- **Scalable Technologies**
  - BLI Effects: Match BL Height to Inlet Height Ratio, Shape Factor
  - Aerodynamic/Propulsive Coupling
    - Effect of Fan Thrust/Mass Flow on Circulation, C_l, C_m, Stagnation Point
      - Approach/Landing Configurations, Climb, High Lift/Angle-of-Attack
    - Adjacent Fan's Thrust/Spillage Level on Neighboring Fan Performance
    - Power Distribution Topology
- **Scaling Challenges**
  - Low Speed Converging vs. High Speed Diverging Inlet
    - Distortion Levels
  - Electric Power Levels
  - Shock Upstream of Inlet at Transonic Speeds

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Project Goals

- Current Program Extends Previous 3 Fan Study
- Goal: Develop 5 Fan Pseudo 3D Configuration With Emphasis on Study of Aero-Propulsive Coupling
- Two Phase Program: CFD Design and Evaluation Followed by Wind Tunnel Investigation
- CFD Design/Analysis
  - Design 5 Fan BLI Inlet System
    - Scale of CFD Model Reflects Wind Tunnel Model Scale
    - Test Conditions Scale to Flying Test Bed Cruise
  - Investigate Effect of Fan Thrust Angle and Thrust Level on Performance and Aero-Propulsive Coupling, Differential Thrust, AOA Effects
- Wind Tunnel Investigation – Low Speed Test (3’x4’ WT)
  - Overall Force/Moment, Surface Pressures
  - CFD Verification, Thrust Level, Differential Thrust, AOA Effects

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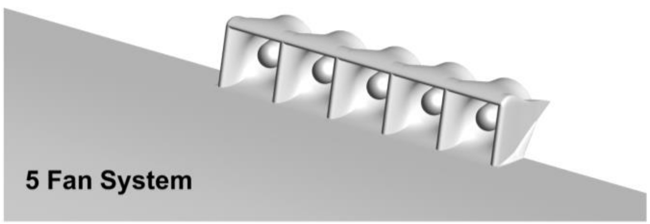
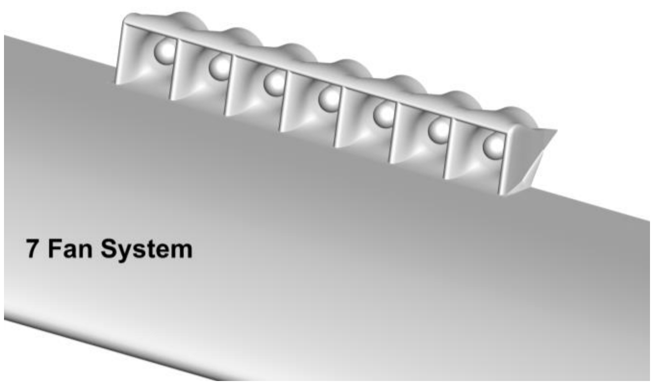
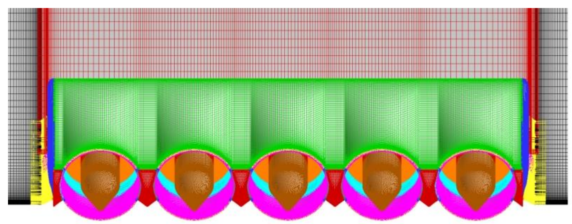
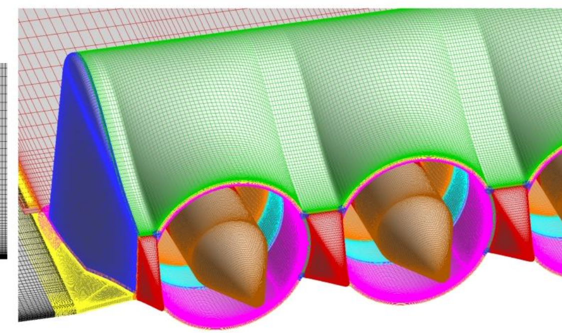
CFD Design

- OVERFLOW Used for Model Design/Analysis
  - All Geometry Generated Using Combination of in House Fortran Routines and Chimera Grid Tools
  - Complete Geometry and Volumes Generated Using an Input File Driven Scripting System
    - 20 Variable Input File: Inlet Width, Height, Location, Fan Radius and Location, Thrust Angle, Cowl Inner/Outer Lip Radius, Cowl Blend Height … etc.
    - Allowed Fast, Parametric Optimization of Inlet Geometry

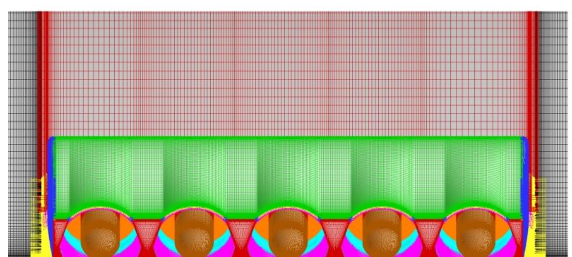


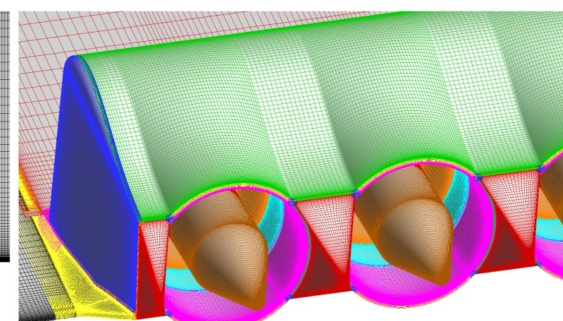






Cowl Fan Blend Height = 45%

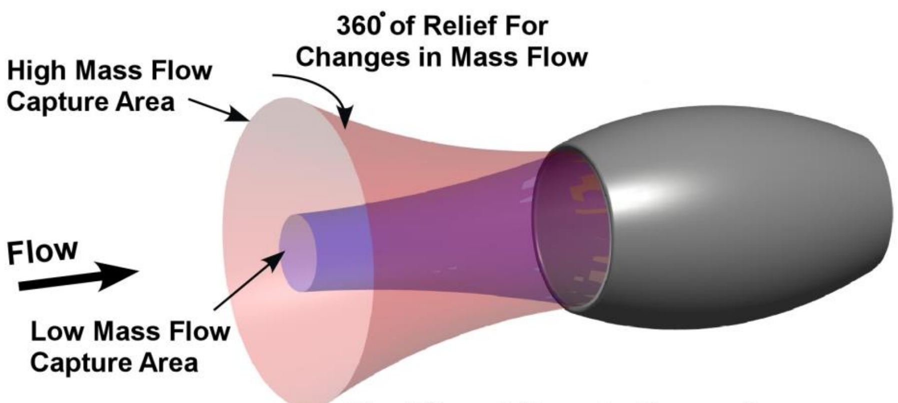




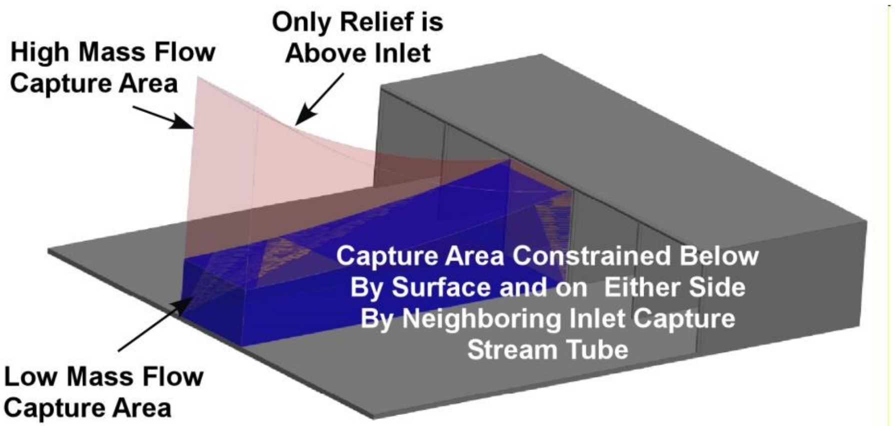
Cowl Fan Blend Height = 70%

Inlet Challenges

- BLI Side-by-Side Multi-Inlet Design Challenges
  - Traditional Inlet
    - 360° of Relief For Changes in Mass Flow
  - Side-by-Side BLI Inlet
    - Capture Area Constrained by Surface and Neighboring Inlets
    - Compromise Design
    - Restriction of Capture Area Can Have Larger Implications For Off Design Spillage Effects



Traditional Nacelle Scenario



BLI Injesting Multi-Fan Distributed Propulsion Scenario

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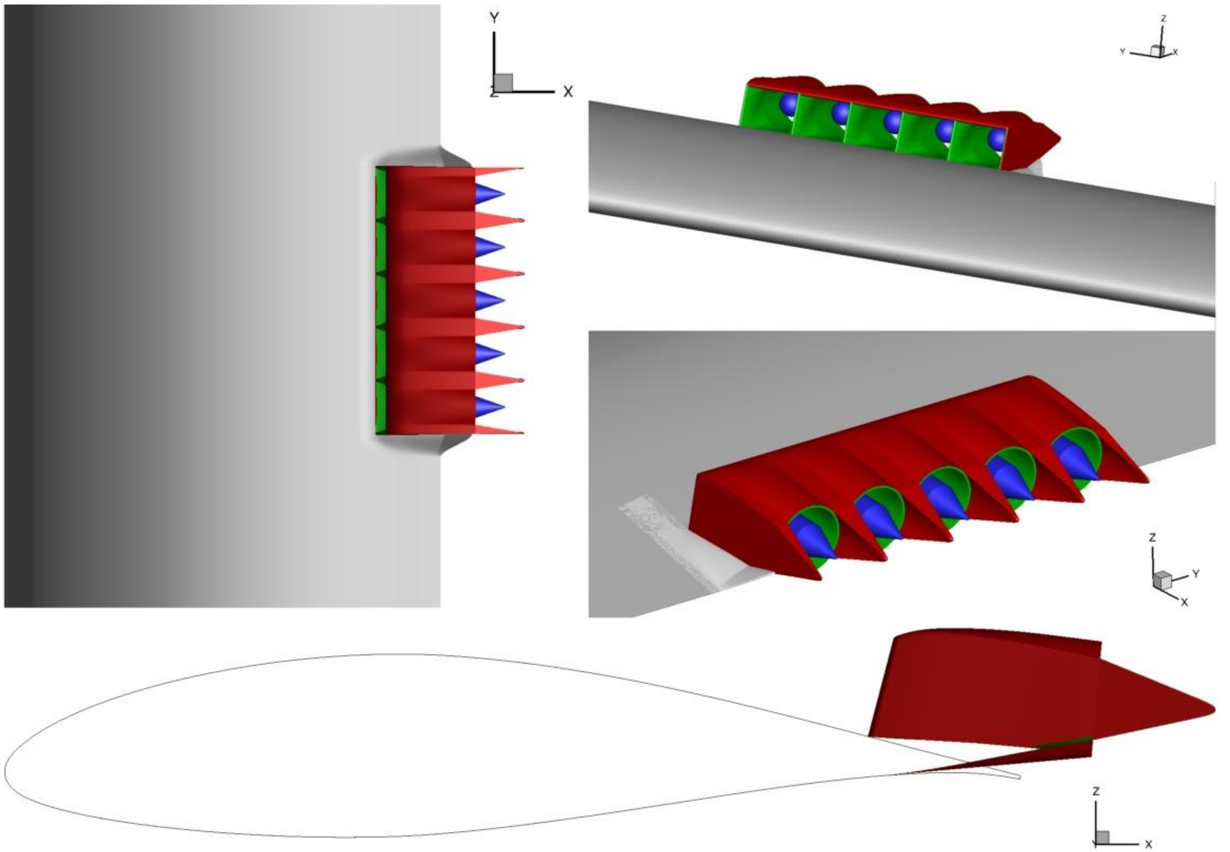
CFD Design

- Conditions
  - Model Scale Based On Wind Tunnel Scale
  - Test Conditions Scale to Flying Test Bed Cruise
  - Inlet at x/c=0.85
    - Want $C_p \geq 0$
  - Inlet Sized For a Weighted Average of Cruise Thrust Required and Thrust Available
    - $T_r \Rightarrow$ Inlet Below $\dot{m}_{Design}$
    - $T_a \Rightarrow$ Inlet Above $\dot{m}_{Design}$
- Fan Sized To Replicate
  - Inlet δ/Fan Diam.
  - Fan Diam./Model Chord

5 Fans, NACA 64_3-618 Section, 20” Chord, 5° Thrust Angle



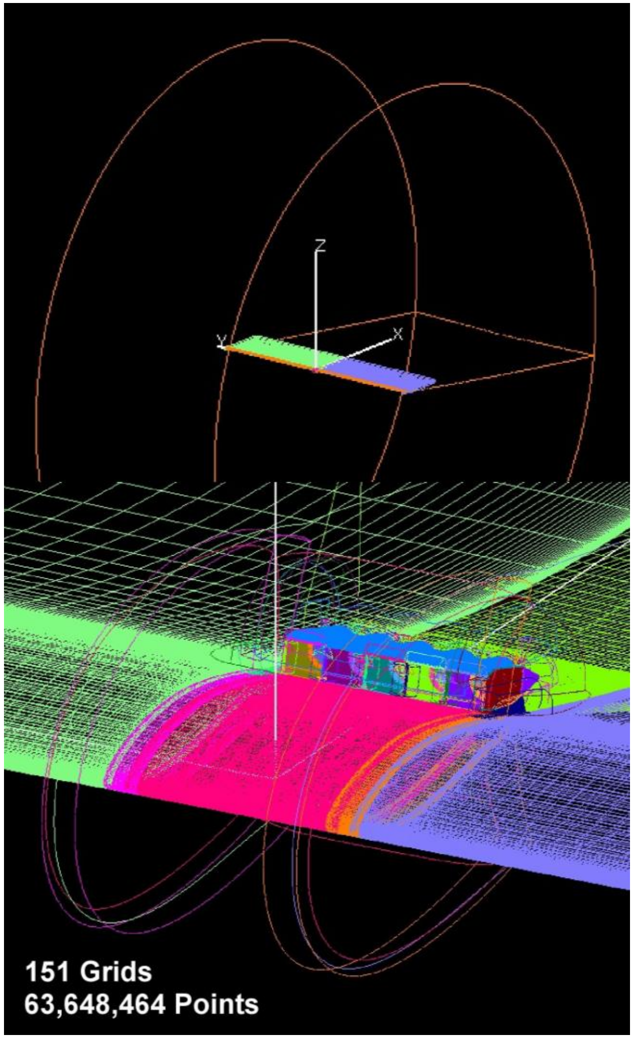
For Model Scale: M=0.09, Re=1.06×10^6

$T_{r,\ per\ fan}$ = 0.33 (lbs), $\dot{m}$ = 0.0067 (slugs/s)

$T_{a,\ per\ fan}$ = 0.74 (lbs), $\dot{m}$ = 0.0084 (slugs/s)

CFD Design

- Grid System
  - Semi-Infinite Straight Wing
- Force/Moment Integration Uses Only Center 5 Fan Section
- Fan Thrust Simulated Using Actuator Disk BC
  - Fan ΔP Adjusted to Achieve Desired Mass Flow/Thrust at α=0°
  - Fan Mass Flow at α=0° Held Constant at Different AOAs (Constant Fan $\dot{m}$ For Polar)
  - No Swirl
    - Fan Does Have a Large Stator Section



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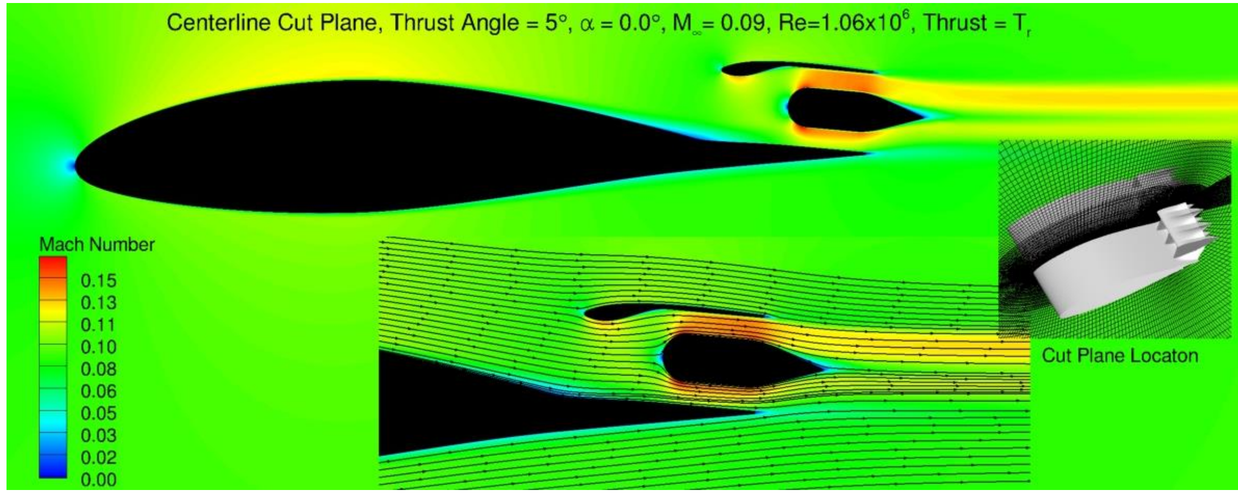
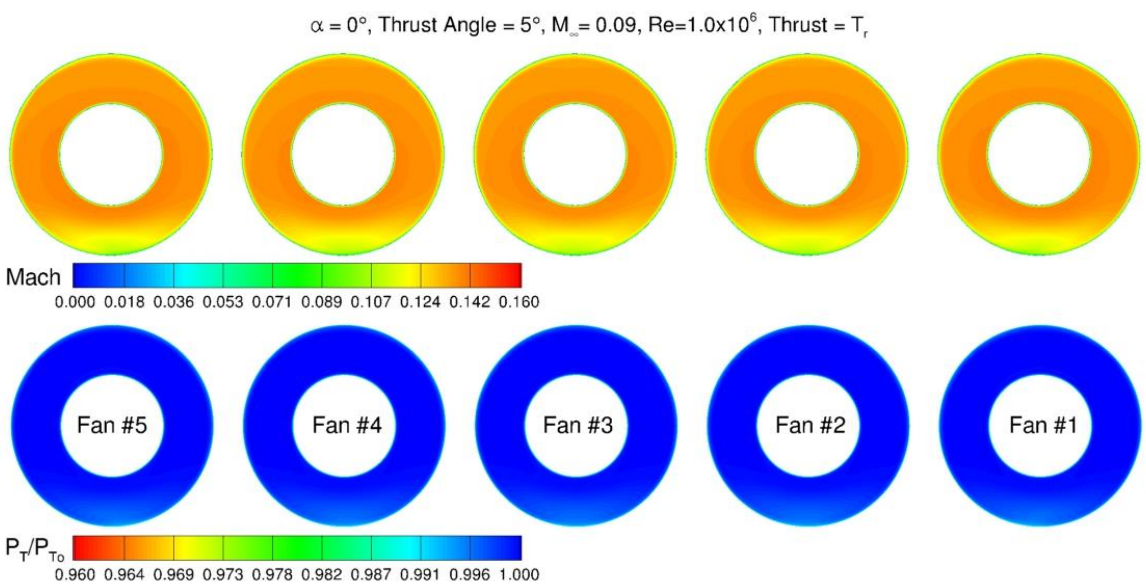
EDF Flowfield

- Centerline Mach Contours & Streamlines
  - No Separation In Duct or On Cowl Surface
- Effect of BLI
  - $\delta/h_{Inlet} = 0.30$
  - BL Effect Continues Through Fan (No Swirl)





- Fan Face Mach & Total Pressure Contours
  - BL Confined to Bottom of Fan Duct (No Swirl)
  - Slight Asymmetry in Mach For Outer Fans Contours
- Very Little Distortion
  - Low Mach #
  - Converging Duct

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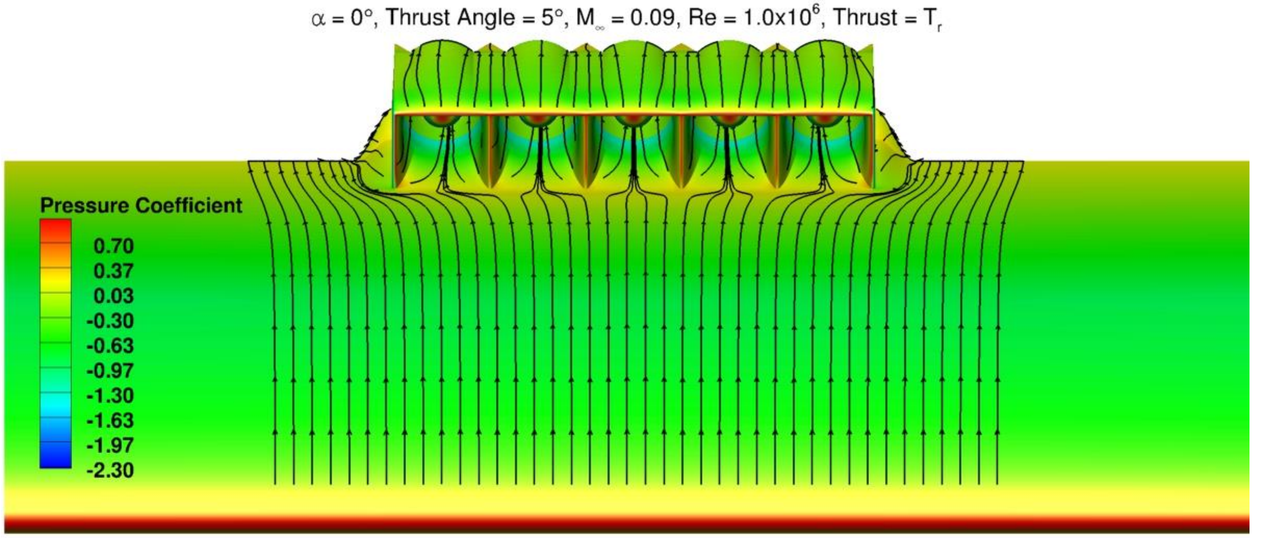
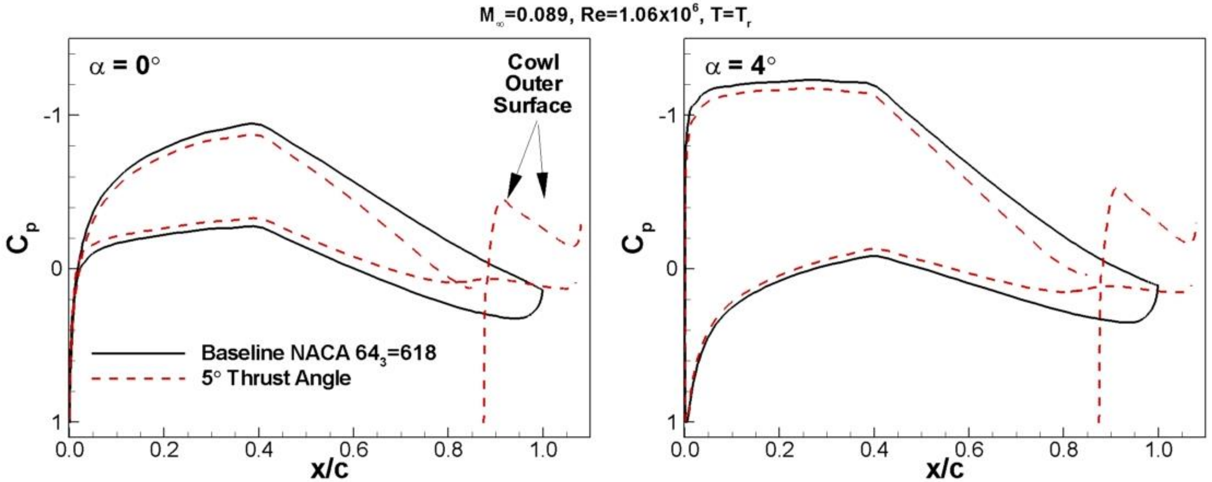
EDF Flowfield

- Pressure Contours & Surface Streamlines
  - At T_r, Mass Flow is Below Inlet Design Mass Flow
  - Low Mass Flow Condition Creates Back Pressure
  - Asymmetry In Outer Fans as Flow Searches For Path of Least Resistance





- Centerline Pressures
  - Change in Section Camber Compared To Baseline NACA 64_3-618
  - Baseline TE Angle ≈ 14.5°
  - Effect of Low Mass Flow Evident in Higher Pressures Upstream of Inlet

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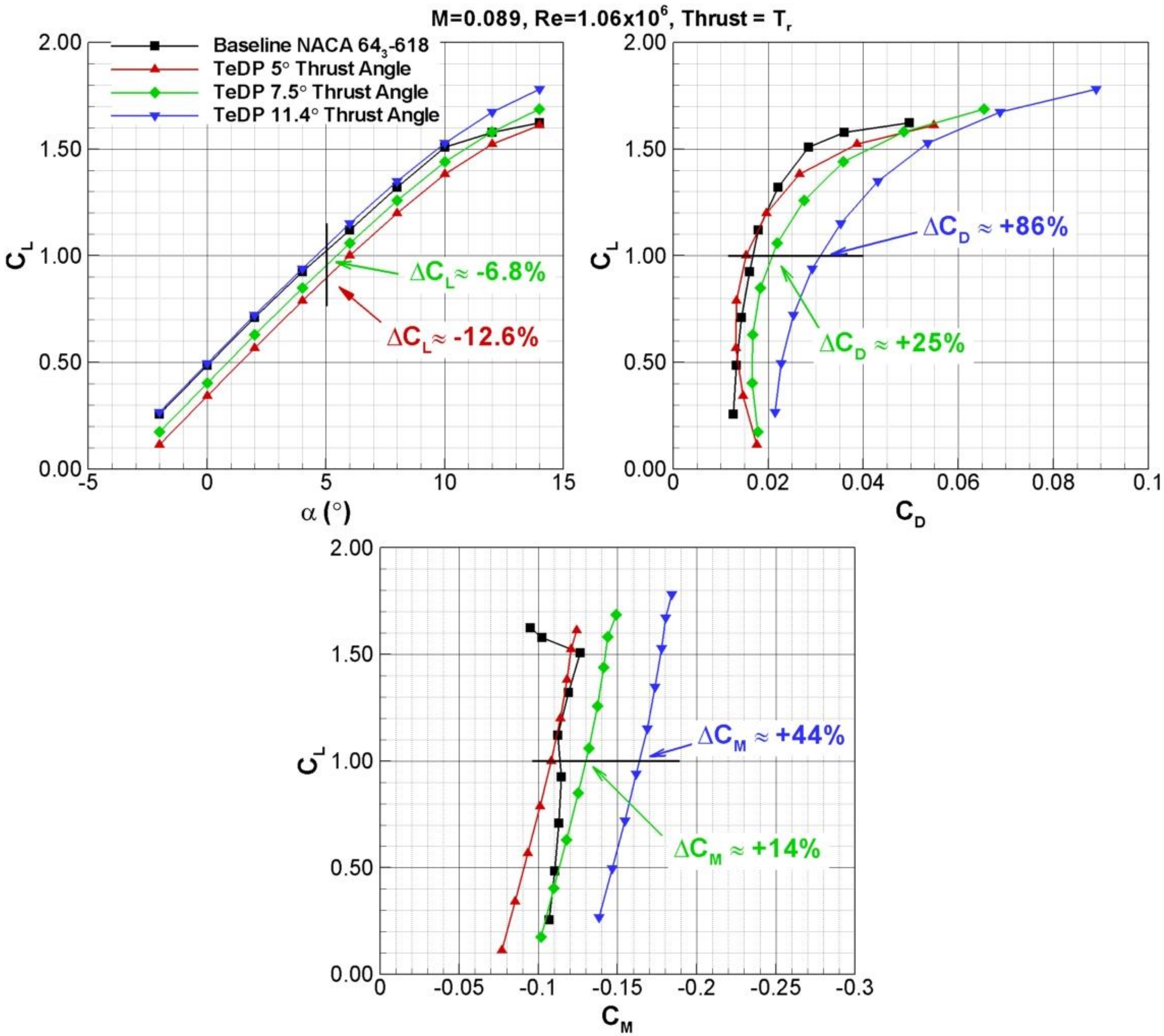
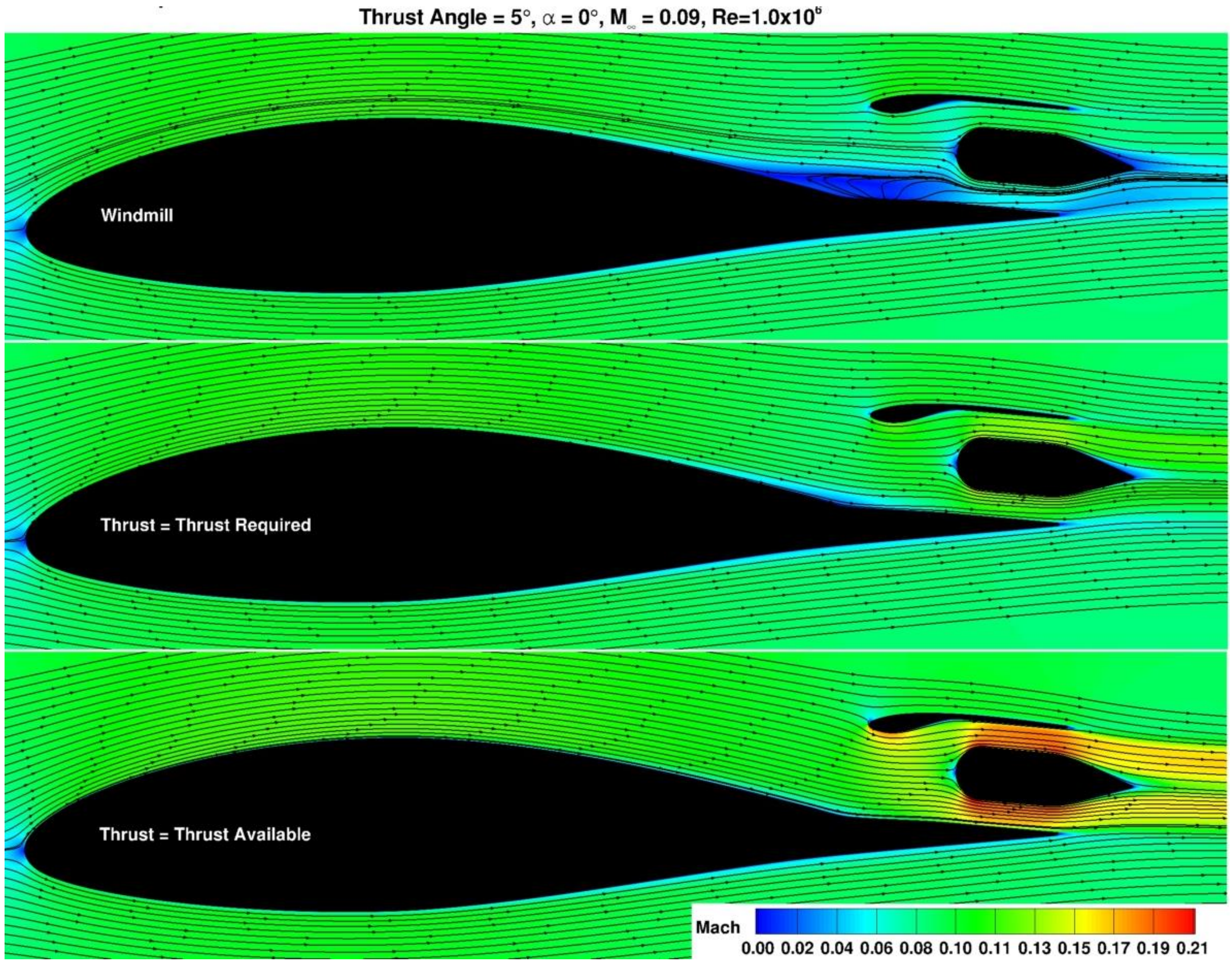
Effect of Thrust Angle

- Thrust ∡ Controls Camber
  - Aft Fan Location Means Increasing Thrust ∡ Increases Camber
  - Increasing Thrust ∡
    - Shifts Lift Curve
    - Increases Nose Down Moment
    - Increases Drag: Primarily Due to Low Cowl Top Pressures – Aft Facing Surface
- 11.4° Thrust ∡ Best Matches Baseline Lift
  - Highest Moment
  - Largest Drag Increase
- 5° Thrust ∡ Most Efficient
  - Best Drag, Moment, Thrust



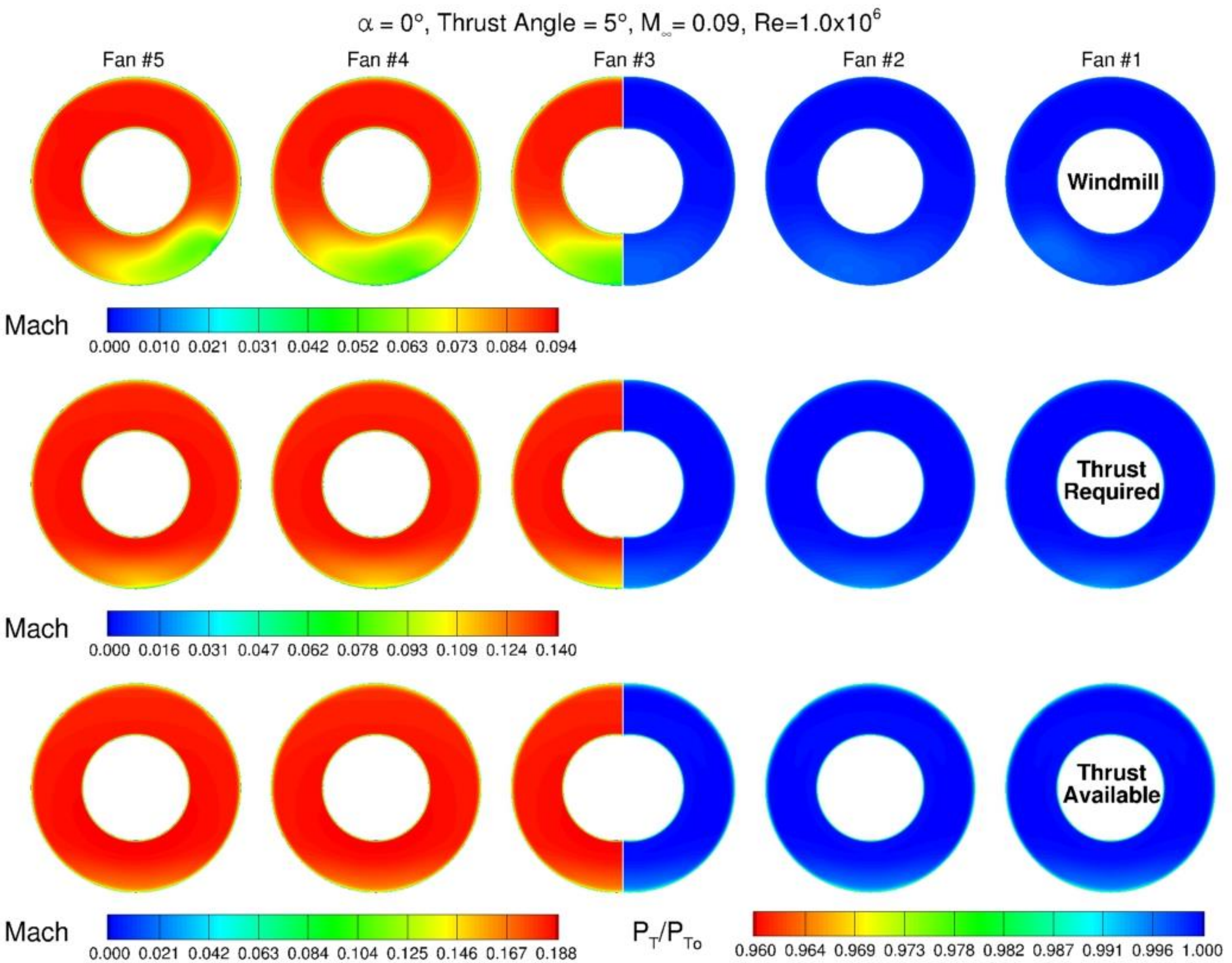
Effect of Thrust Level

- Inlet Capture Area
  - Sized For a Mass Flow Between T_r and T_a
- Windmill
  - Blockage Creates Large Separated Region Upstream
  - Cowl Remains Attached
- Thrust Required
  - $V_{Inlet}=0.81V_{\infty}$
  - $\delta/h_{Inlet} = 0.30$
- Thrust Available
  - $V_{Inlet}=1.10V_{\infty}$
  - $\delta/h_{Inlet} = 0.23$



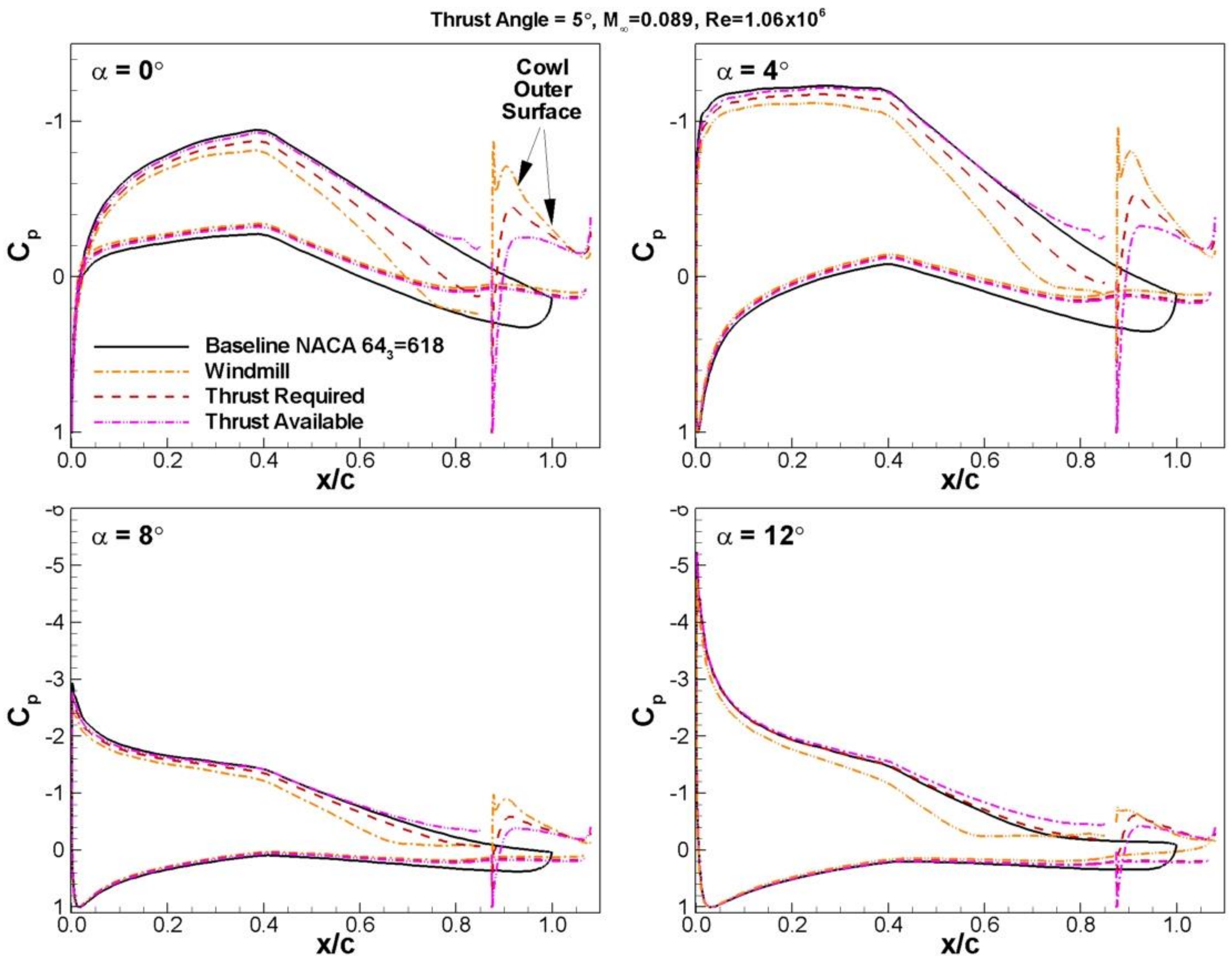
Effect of Thrust Level

- Mach Contours
  - Show Decreasing BL Height With Incr. Mass Flow
  - Show Increasing Symmetry With Incr. Mass Flow
- Total Pressure Contours
  - Very Little Distortion, Even For Windmill Case
    - Low Mach #
    - Converging Inlet



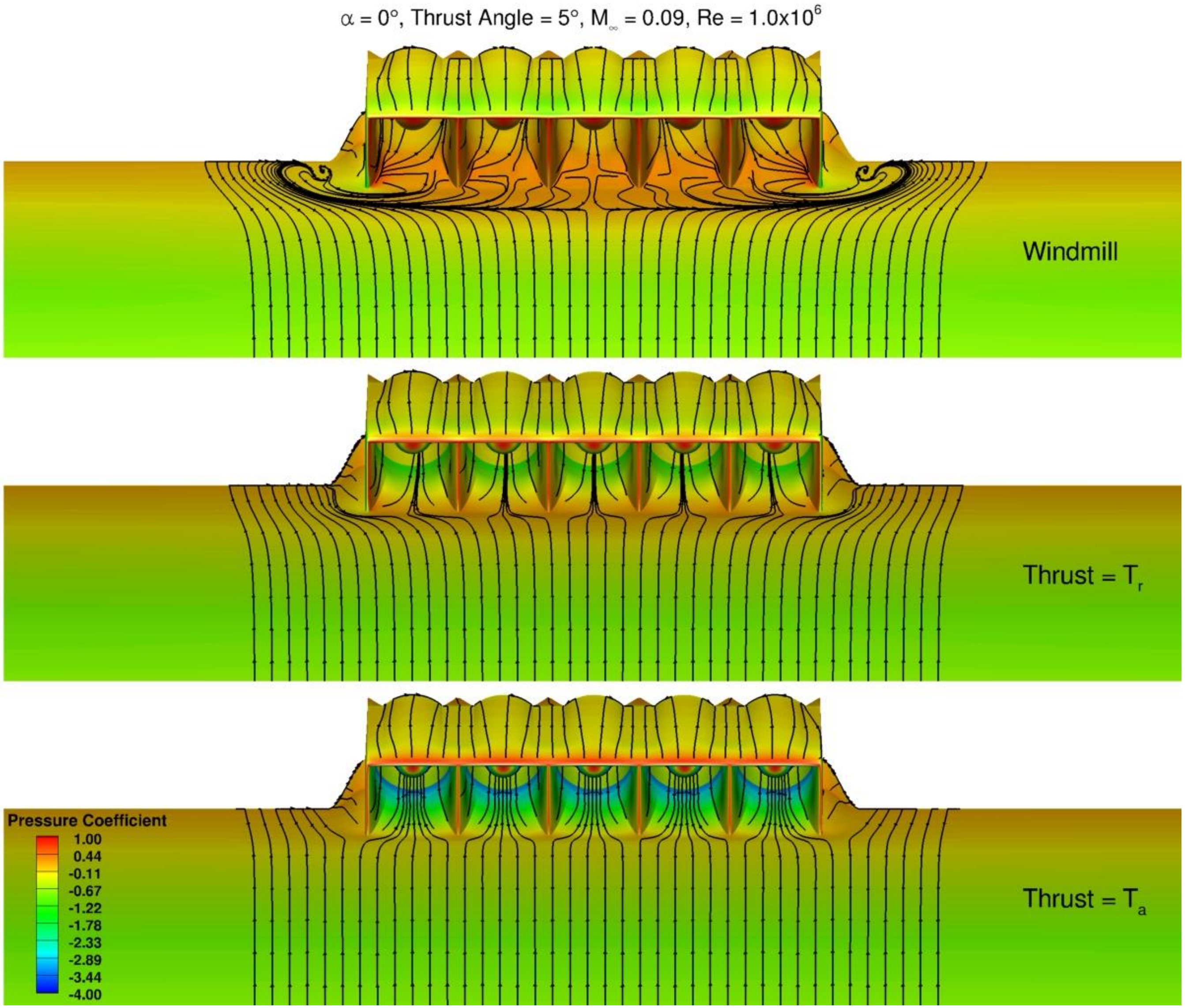
Effect of Thrust Level

- Windmill
  - Blockage Creates Large Separated Region Upstream
- Thrust Required
  - Below Design $\dot{m}$
  - $V_{Inlet}=0.81V_\infty$
- Thrust Available
  - Above Design $\dot{m}$
  - $V_{Inlet}=1.10V_\infty$

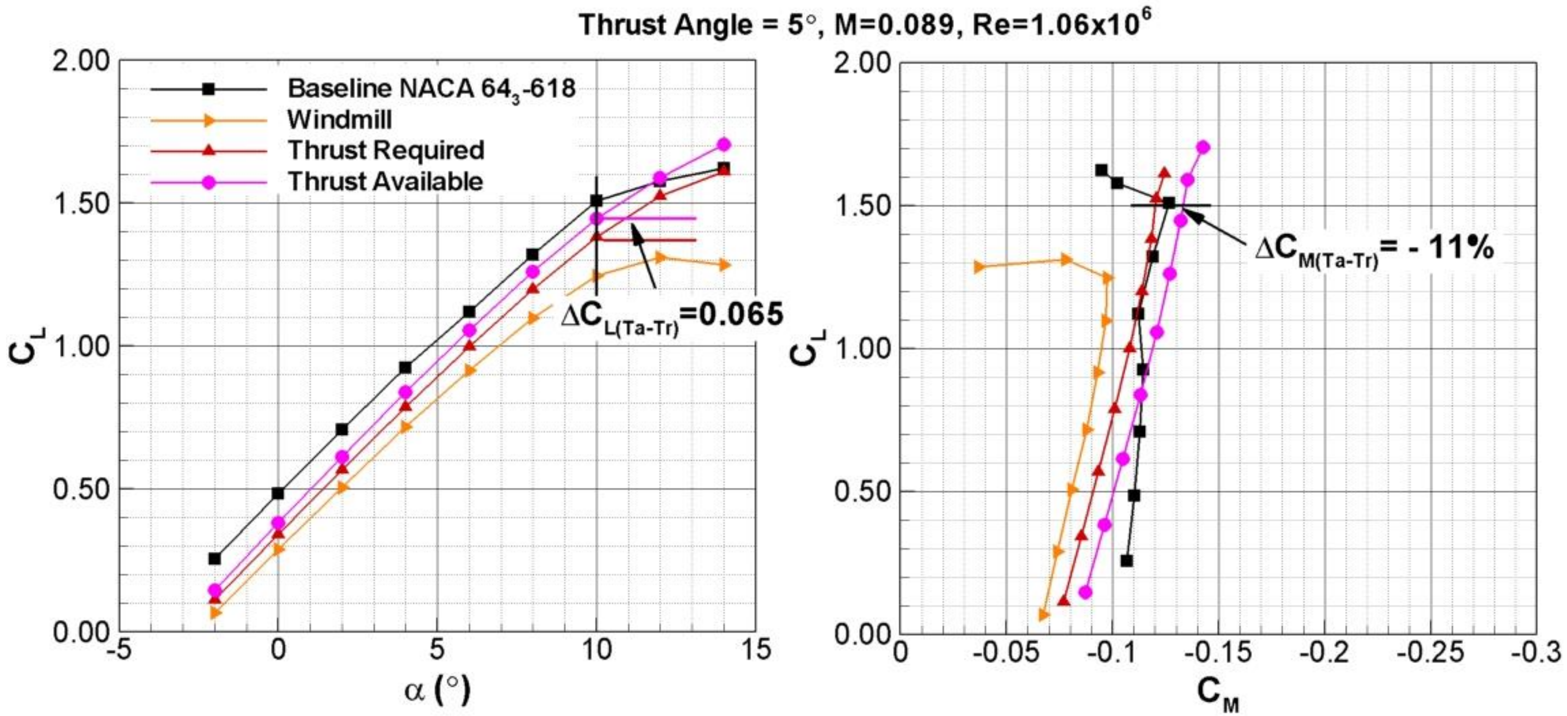


Effect of Thrust Level

- Windmill
  - Blockage Creates Large Separated Region Upstream
  - Flow Primarily Attempts to Move to the Outside
  - Attached Cowl
- Thrust Required
  - Below Design $\dot{m}$
  - Slight Asymmetry in Outer Fans
- Thrust Available
  - Above Design $\dot{m}$
  - Good Fan-to-Fan Symmetry



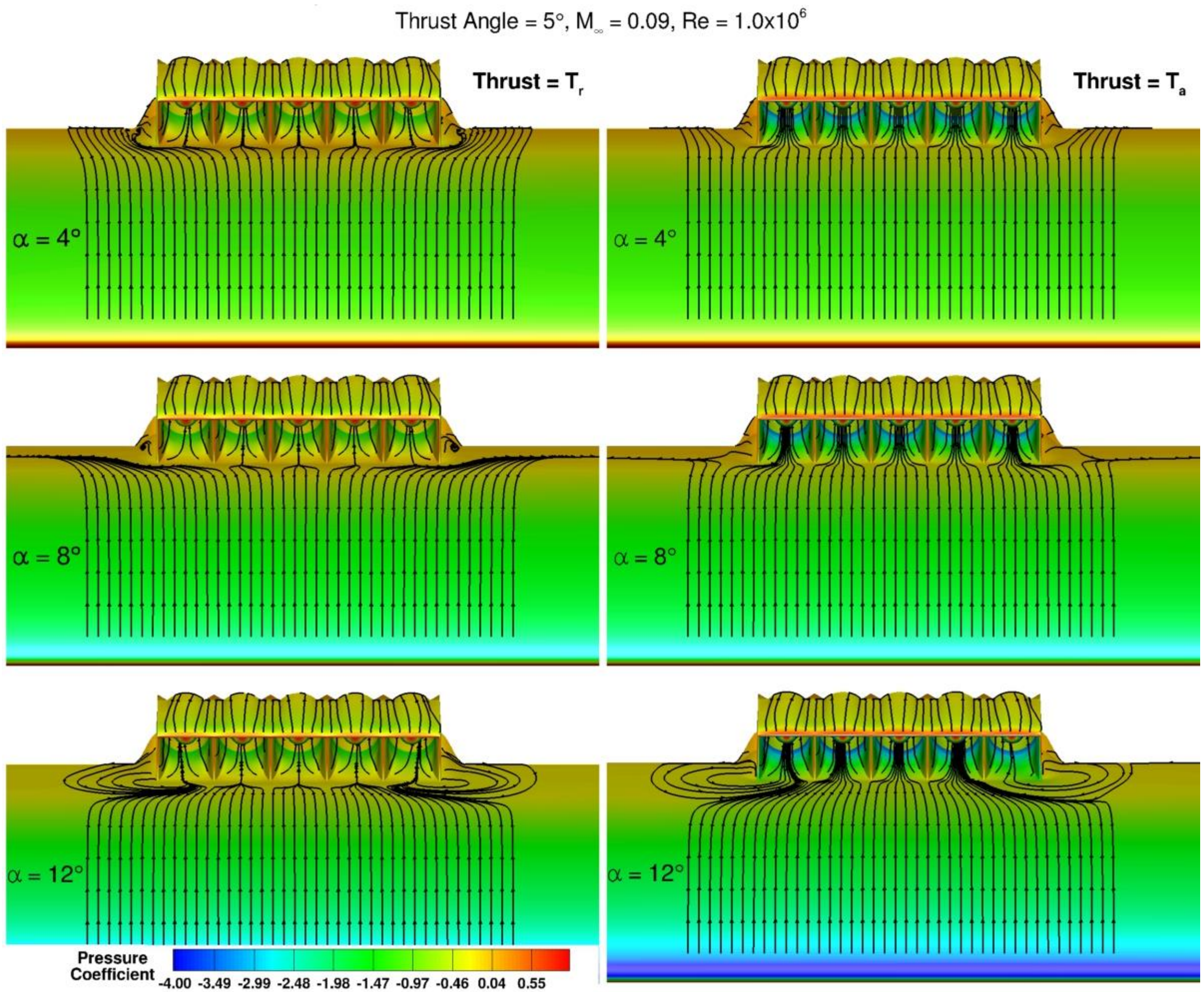
Effect of Thrust Level



- Increasing Thrust Level/Mass Flow Increases Effective Camber
  - Combination of Increased Thrust Vector in Lift Direction and Thrust Based Circulation Effect
    - At $\alpha = 10°$, $\Delta C_{L(Ta-Tr)} = 0.065$, Lift Based Thrust Vector Only Accounts For $\Delta C_L = 0.015$
- Windmill Results Most Likely Optimistic
  - Presence of Fan in Actual System Would Increase Blockage
- Increasing Thrust Level/Mass Flow Increases Nose Down Moment

Effect of Thrust Level

- Ingestion of BL by Fans Postpones Separation For Powered Cases
- Baseline Section Separation Effects Outer Fan Flowfield
  - Baseline Section Exhibits Small Near-Wall TE Sep. at $\alpha=8^\circ$
  - Separation Grows and Moves Forward With Increasing α
- Loss of Lift at Higher C_Ls Due To Interaction of Outer Fans With Baseline Separation



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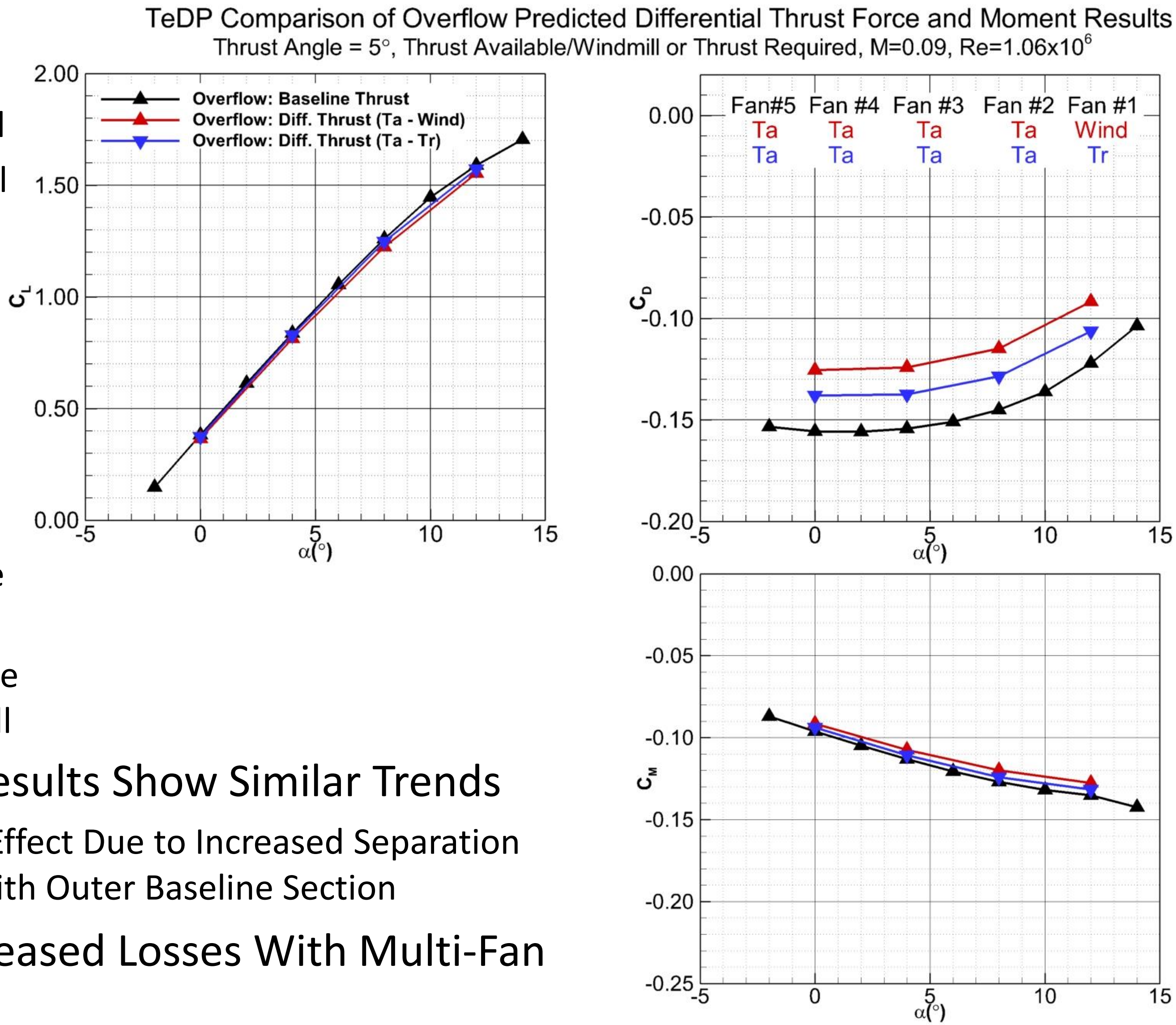
Differential Thrust

- Differential Thrust Cases Investigated
  - T_r T_r T_r T_r Windmill
  - T_a T_a T_a T_a Windmill
  - T_a T_a T_a T_a T_r
- For F&M Results, Largest Effect On Drag
  - Small Loss In C_L and Reduction in C_M
  - Primarily an Increase in C_D
  - Losses Optimistic Due to no Fan in Windmill

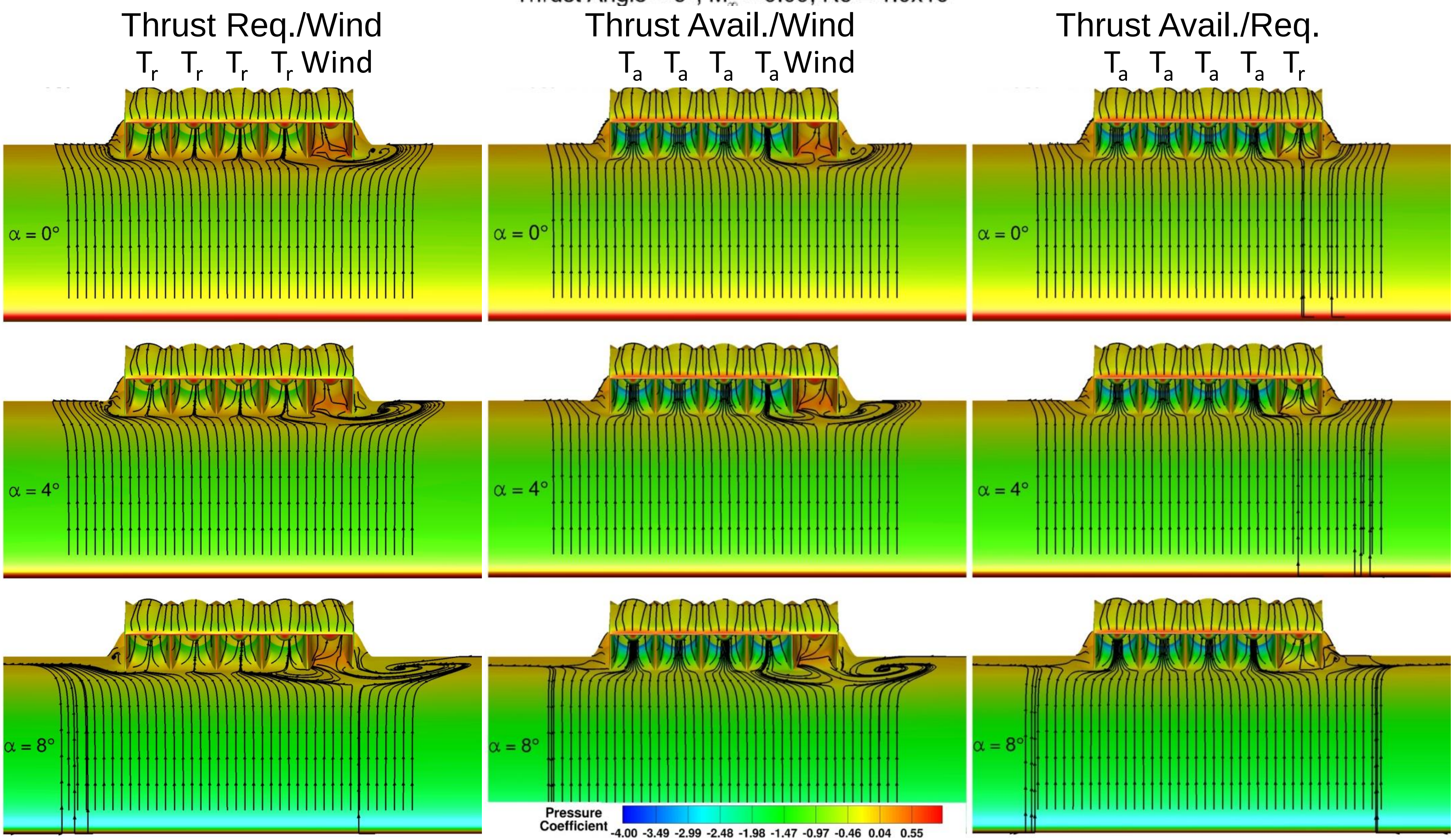


- Thrust Required Results Show Similar Trends
  - Slight Increase in Effect Due to Increased Separation and Interaction With Outer Baseline Section
- Would Expect Increased Losses With Multi-Fan Differential Cases

Differential Thrust

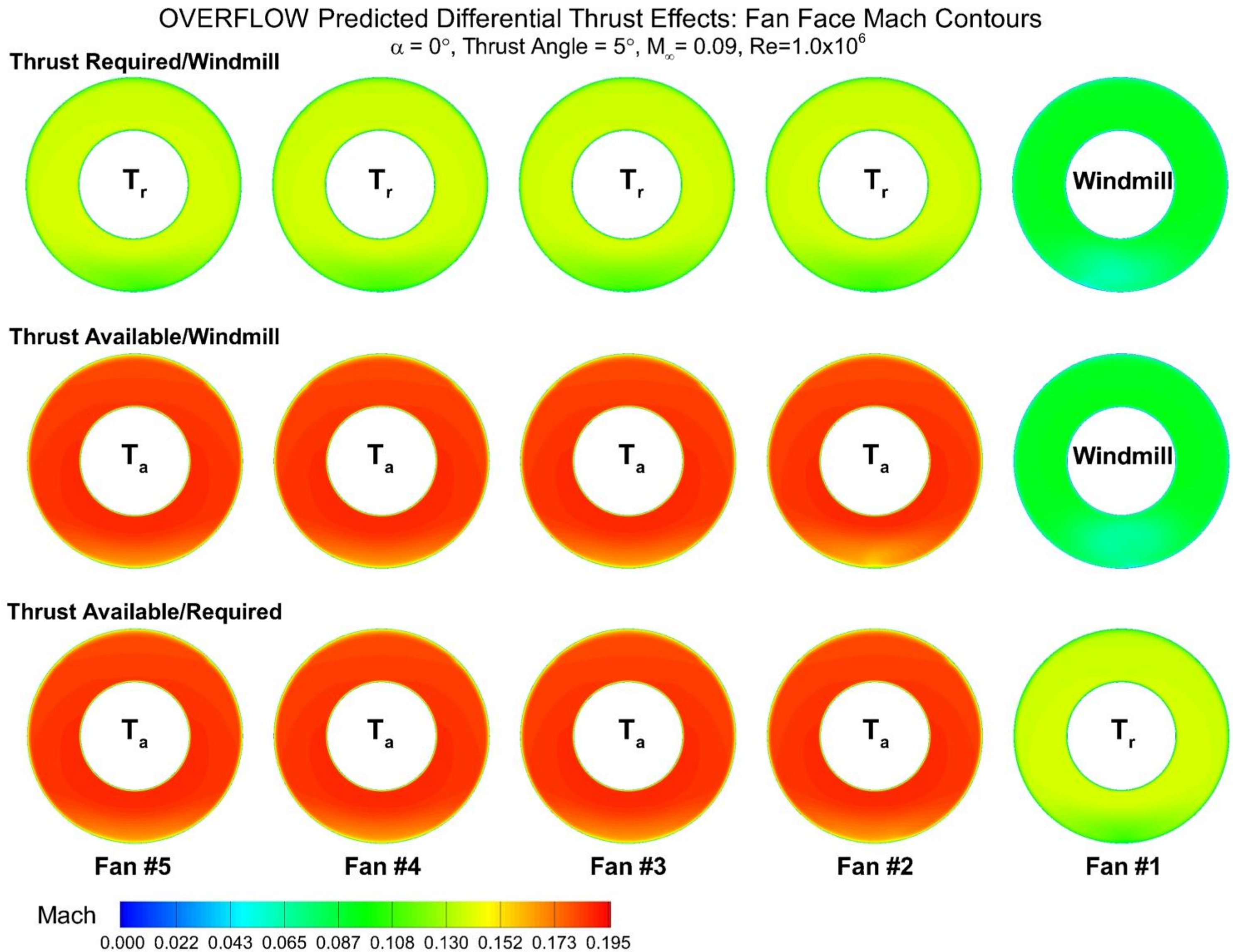
Effect of Diff. Thrust and α on OVERFLOW Predicted TeDP Model Surface Pressures and Streamlines

Thrust Angle = 5°, M_∞ = 0.09, Re = 1.0x10[6]



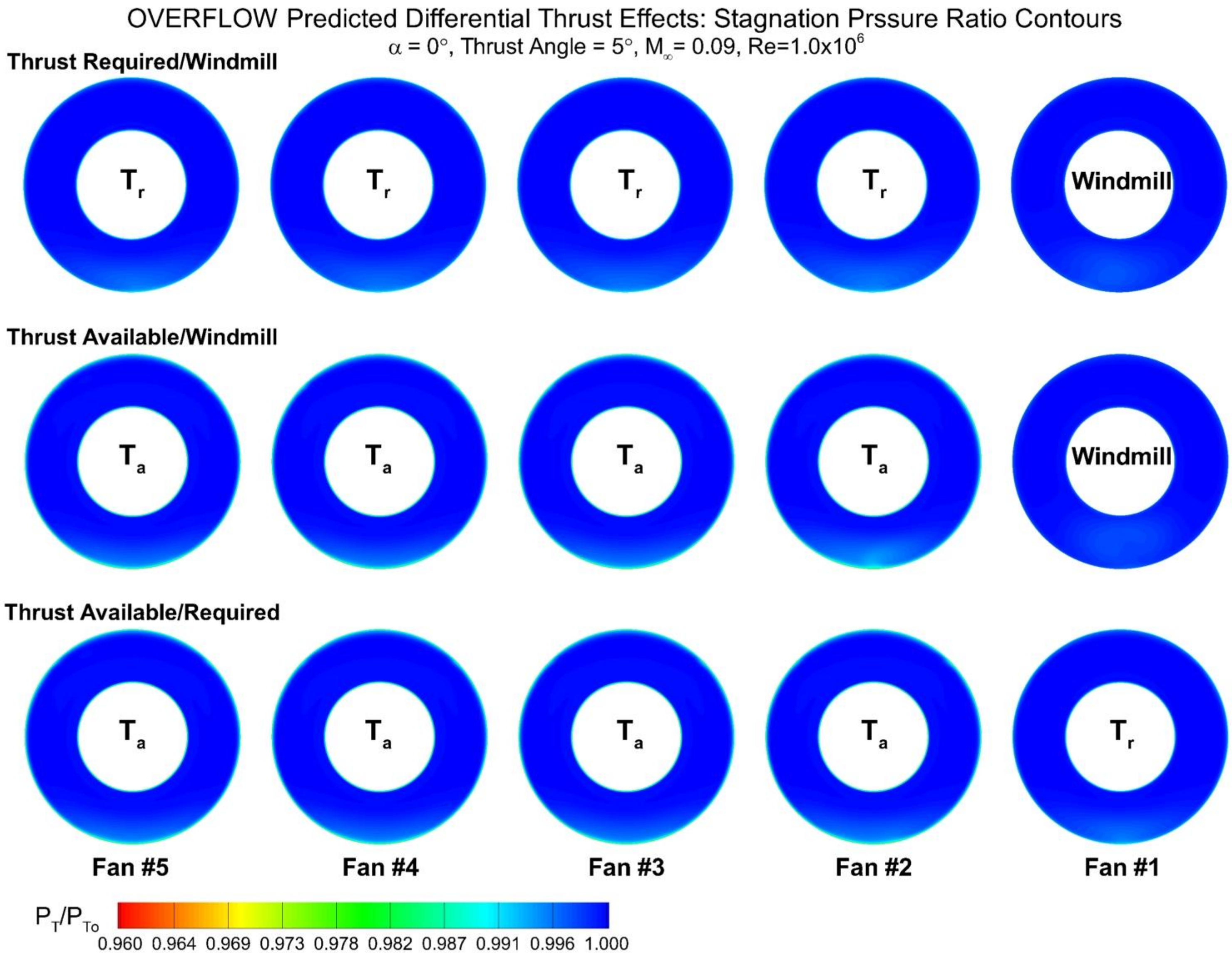
Differential Thrust

- Large Separation Upstream of Windmill Inlet Has Minor Effect on Neighboring Fan Face Contours
  - Largest Effect For Thrust Available – Windmill Case
- Centerline Fan Contours Unaffected
- Reduced Mass Flow Effect Confined to Adjacent Fan



Differential Thrust

- As Has Been Observed Throughout Study, Very Little Stagnation Pressure Loss at Fan Face
  - Low Mach # Combined With Converging Inlet
- Largest Effect For Thrust Available



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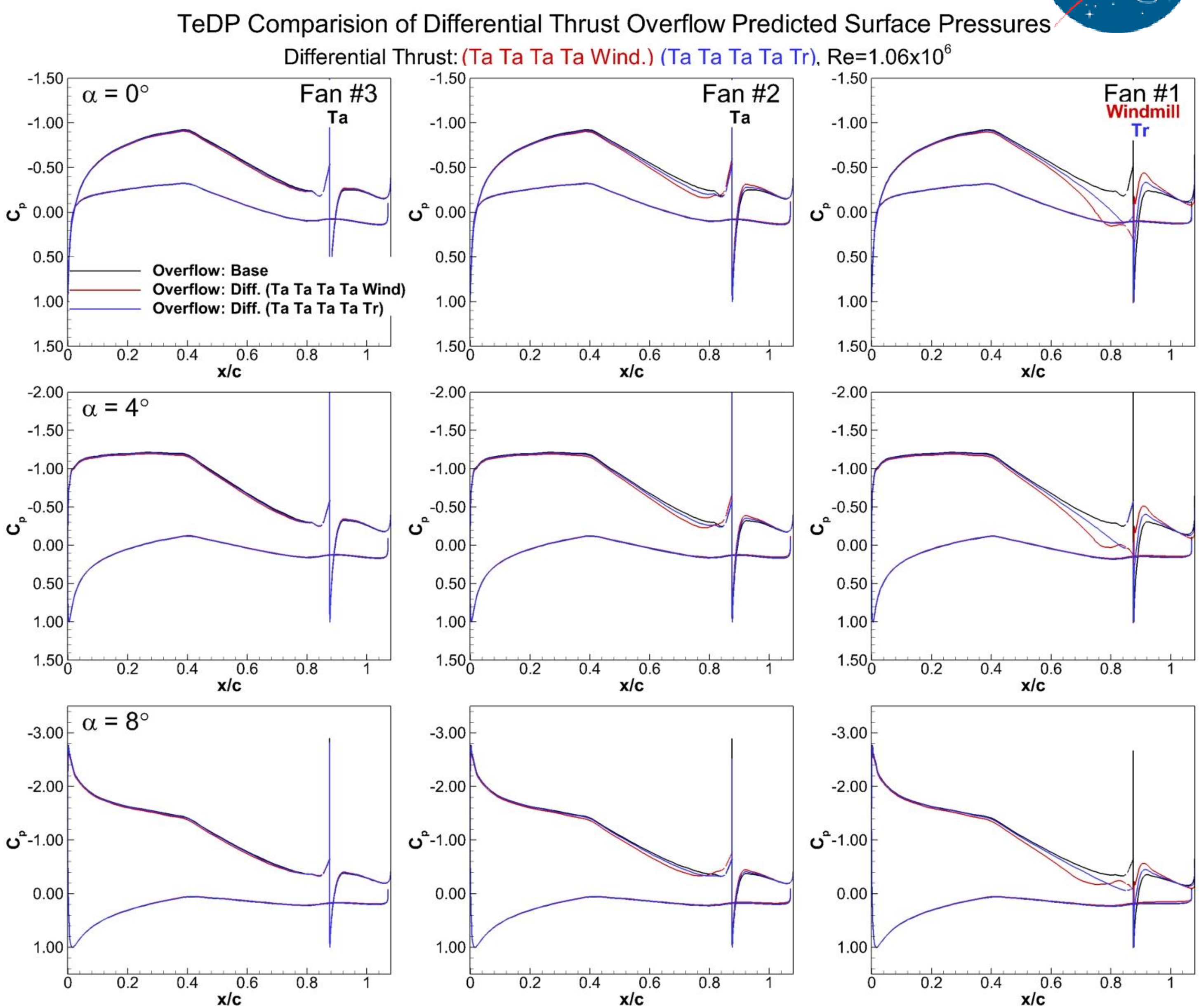
Differential Thrust

- Significant Impact Observed In Reduced Mass Flow Fan Pressures
- Minor Impact Observed In Adjacent Fan Pressures
- Center Fan Essentially Unaffected
- Reduced Mass Flow Effect Confined to Adjacent Fan



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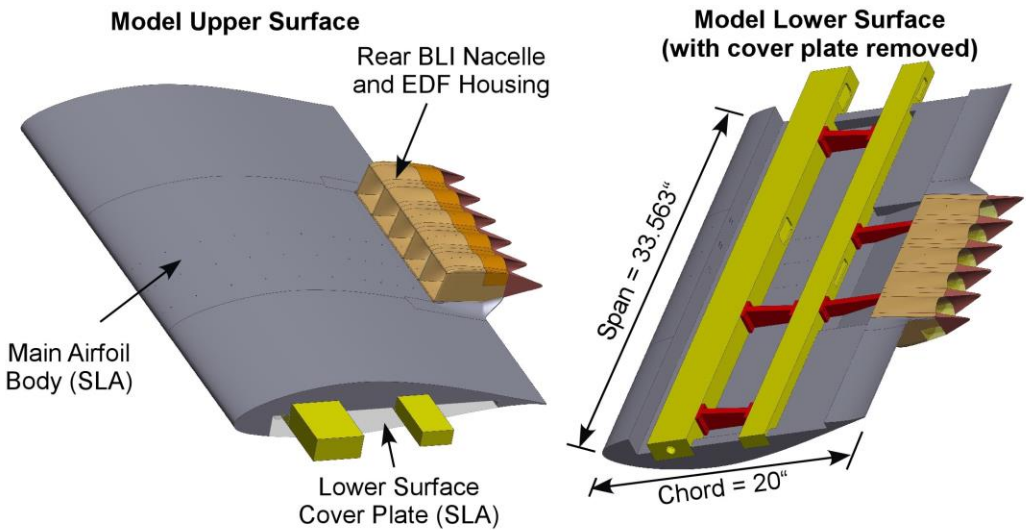
CFD Conclusions

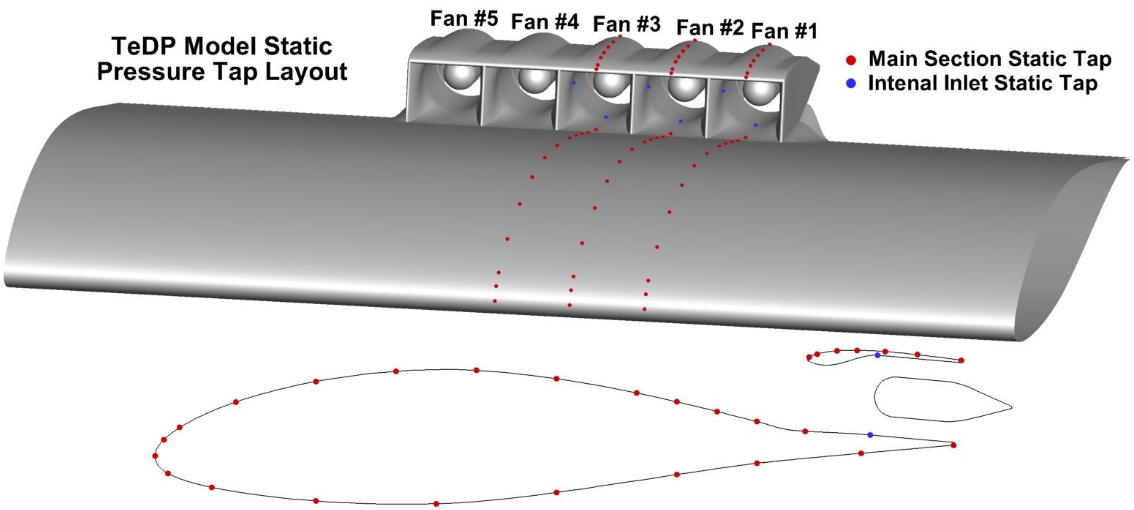
- Thrust Angle Effects
  - Fan Thrust Angle Directly Affected Section Camber
  - Higher Thrust Angle Geometries Produced Large Drag and Moment Increases
    - Large Drag Increases Primarily a Result of Increased Pressure Drag on Cowl Surface Due to Cowl Rotation (Aft Facing Surface)
  - 11.4° Thrust Angle Best Matched Baseline Section Lift Curve
  - 5° Thrust Angle Most Efficient Geometry: Best Match of Baseline C_D and C_M
- Thrust Level Effects
  - ΔC_L of 5-6% and ΔC_m of 10% Were Observed Between T_r and T_a Cases
    - Changes Were Primarily a Result of Mass Flow Based Circulation Effects
    - Smaller Than Anticipated
  - Asymmetries in Inlet Flowfield Were Observed as a Function of α
    - Due to BLI, Fan Flowfield Tends to Remain Attached
    - Separation Generated By Baseline Section On Either Side of Fan Section Was Observed to Interact With Outer Fan Flowfields
- Differential Thrust Effects
  - Force/Moment: Drag Primarily Affected With Slight C_L Reduction
  - Pressures and Fan Face Results Show Reduced Fan Mass Flow Effect is Confined to Adjacent Fan and Does Not Propagate Beyond Adjacent Fan

Final Tunnel Test

- Final Verification Wind Tunnel Test Performed
  - University of Illinois at Urbana-Champgain 3 ft x 4 ft Tunnel
- Test Examined Multi-Fan Effects on Aerodynamic/Propulsive Coupling, BLI, Circulation and Angle-of-Attack
- Effect of Fan Thrust Level and Mass Flow on:
  - Overall Wing and Sectional Aerodynamic Characteristics
  - High Angle-of-Attack Behavior: Separation Location, Characteristics, and Progression
  - Spanwise Differential Thrust: Effect of Changing Fan Mass Flow and Spillage on Adjacent Fan Flowfield and the Extent to Which Those Effects are Propagated
- Model Mimicked 3D CFD
  - 5 Fan BLI System Mounted on Center of 2D Model
  - Model Spanned Tunnel Height
  - Stereo Lithography Skin With Stainless Spars/Ribs



Test Set-Up



- 3 Axis Force Balance
  - Lift, Drag, Moment
- Surface Pressures
  - 3 Rows (Fans #1, #2, #3)
  - Internal Duct Pressures
    - Calibrate Fan RPM/Mass Flow to Match CFD Conditions
- Fans: Hyperflow 56 EDF
  - R/C Hobby EDF (1.9 lbs Static Thrust/Fan, 15 V at 32 Amps, 50,000 RPM)
  - Fans Run From DC Power Supply
    - Motor/Controller Heating Issues
    - Water Cooled Controllers
    - Heating Issues Related to Power Supply?
- Could Not Obtain 5-Hole Wake Data
  - Planned to Map Wake With 5-Hole Probe
  - Runs Required 5+ Hours For Single AOA
  - Heating Issues Reduced Max Run Times to Several Minutes

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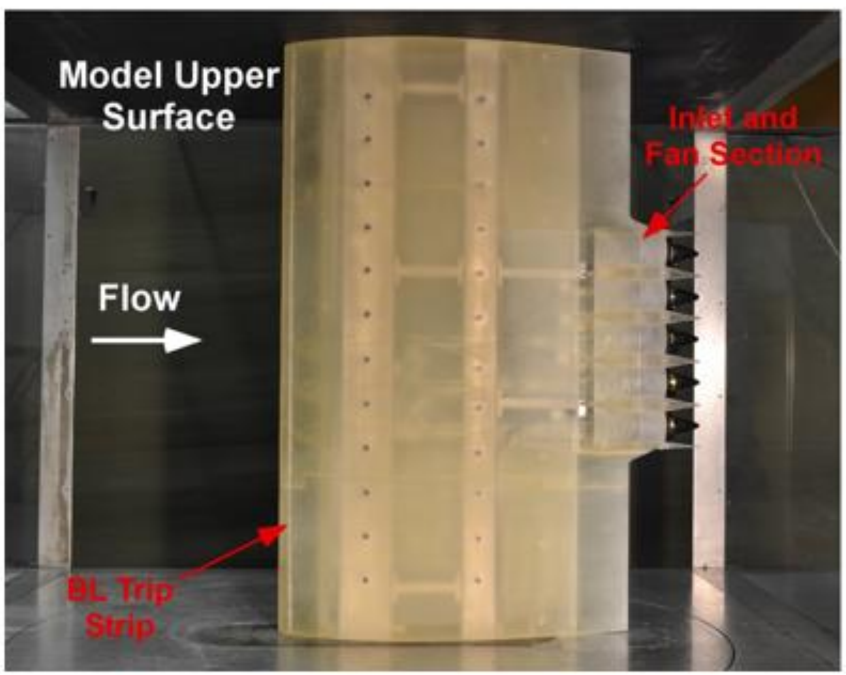
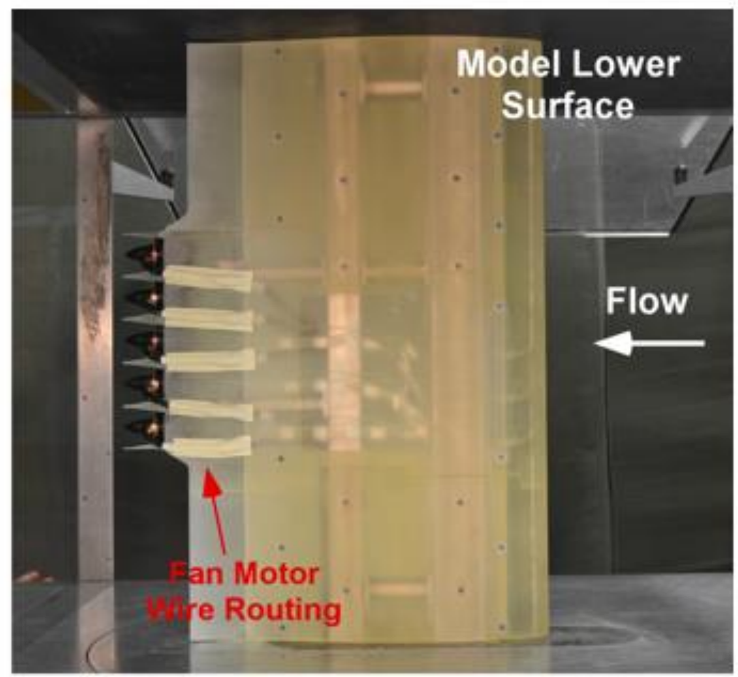
Test Set-Up

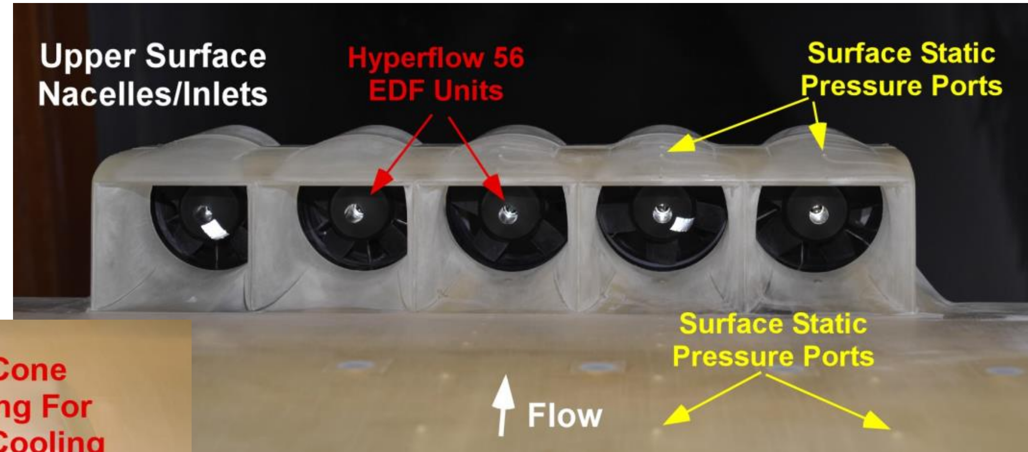
- Fans Computer Controlled (National Instruments LabView)
  - Measured Fan RPM, Motor Amperage/Power, Motor/Controller Temperature
- Floor Balance: Lift, Drag, Pitching Moment
- Surface Pressures: DTC Initium System
- Due To Small EDF Size Motor Wires Had to be Routed Externally
  - Primarily Drag Increase

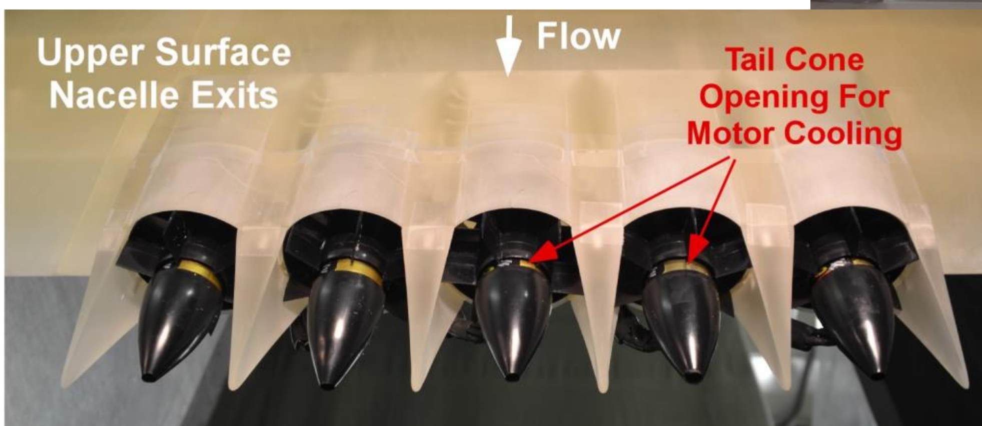


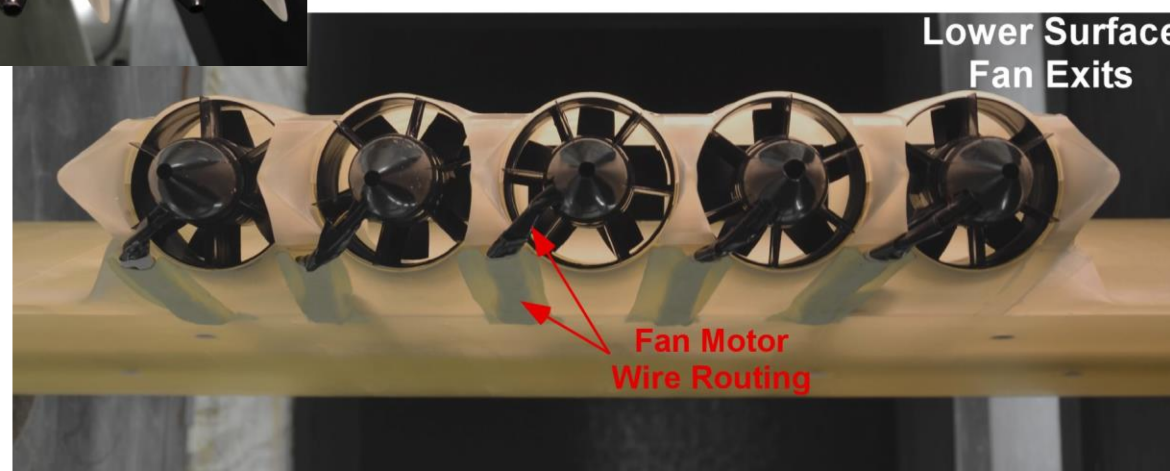


Test Set-Up

- Nacelle/Fan System Installed Photographs







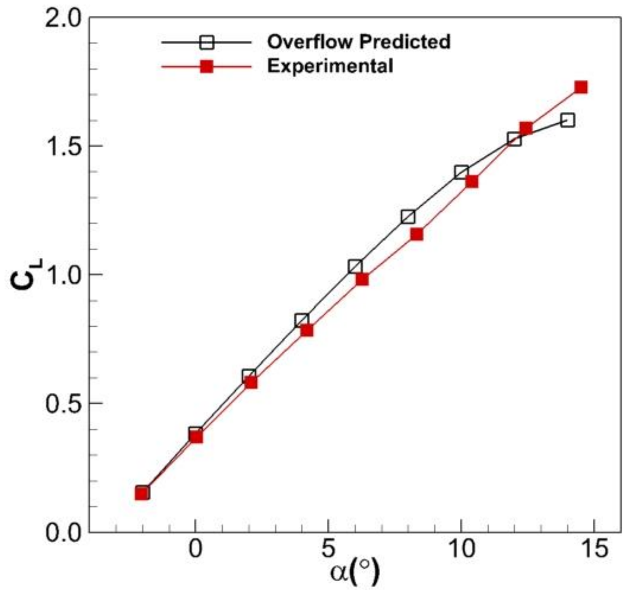
Test Conditions

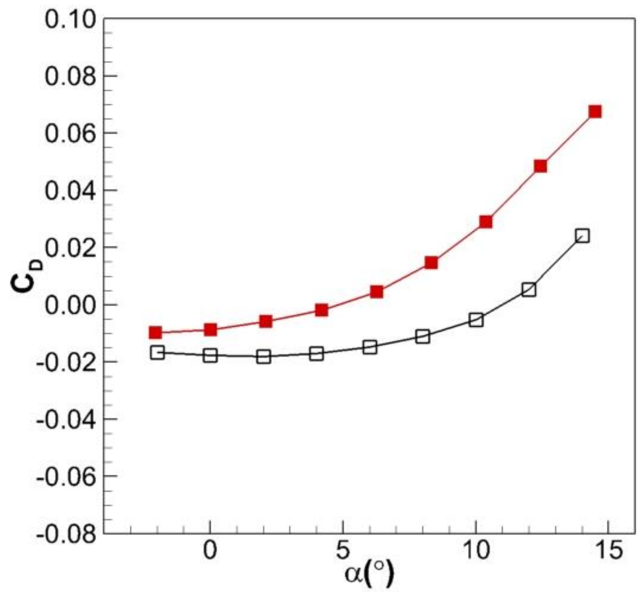
- Conditions Run to Match CFD Based on Test Bed Cruise Thrust Required and Thrust Available Fan Mass Flows
  - Fan Throttle Calibrated Using Internal Duct Pressures
    - Fan Throttle versus Duct and Surface Pressures
  - $M=0.09$, $Re=1.06\times10^6$
- AOA Polars, α = -2° to 14 °
  - Thrust Required Mass Flow (T_r = 30% Throttle, Fan RPM ≈ 33,000)
  - Thrust Available Mass Flow (T_a = 80% Throttle, Fan RPM ≈ 42,500)
  - Windmill Condition
- Differential Thrust Polars
  - Abbreviated AOA Polar, α = 0°, 4 °, 8°, 12°

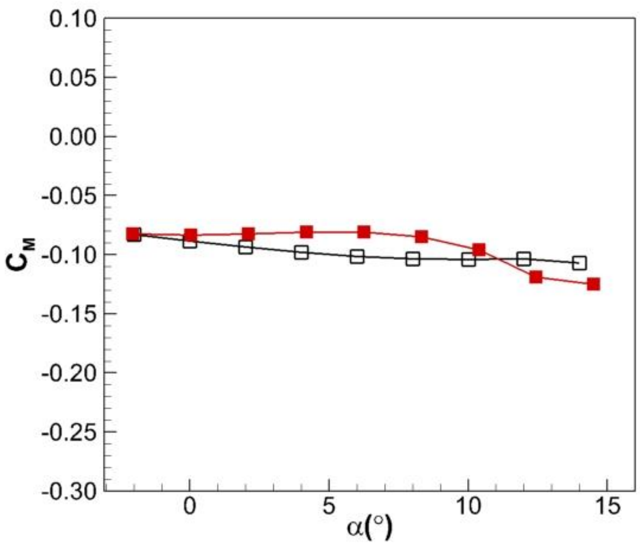
	Fan #5	Fan #4	Fan #3	Fan #2	Fan #1
Thrust Level	T_r	T_r	T_r	T_r	Windmill
	T_a	T_a	T_a	T_a	Windmill
	T_a	T_a	T_a	T_a	T_r
	T_r	T_r	T_r	Windmill	Windmill
	T_r	T_r	Windmill	T_r	T_r

Thrust Required Results

- Good C_L Match at Low AOAs
- CFD Over Predicts C_L at Mid AOAs
  - At $\alpha = 4°$, ΔC_L=0.05
  - At $\alpha = 8°$, ΔC_L=0.10
- No C_L Break at High α For Exp. Data
- Exp. C_D Higher Than CFD
  - Discrepancy Grows With α
  - External Wire Routing
    - Fan Wires in Thrust Stream
    - Lower Surface Routing Into Model
  - Sidewall Horseshoe Effects
- C_{Mo} Well Predicted at Low α
  - Trend With α Off
    - C_M Difficult to Match (Sidewall Effects)



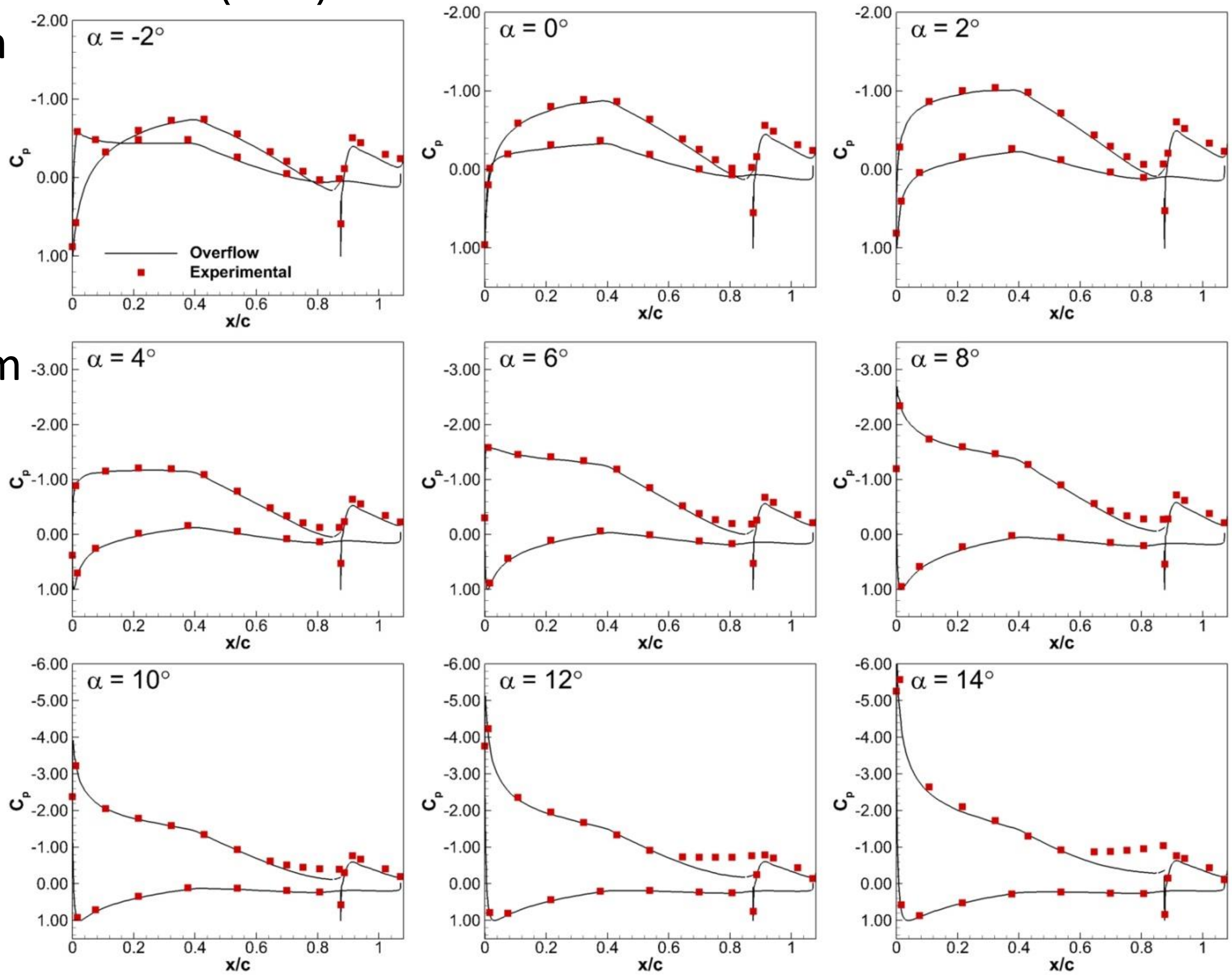




Thrust Required Results

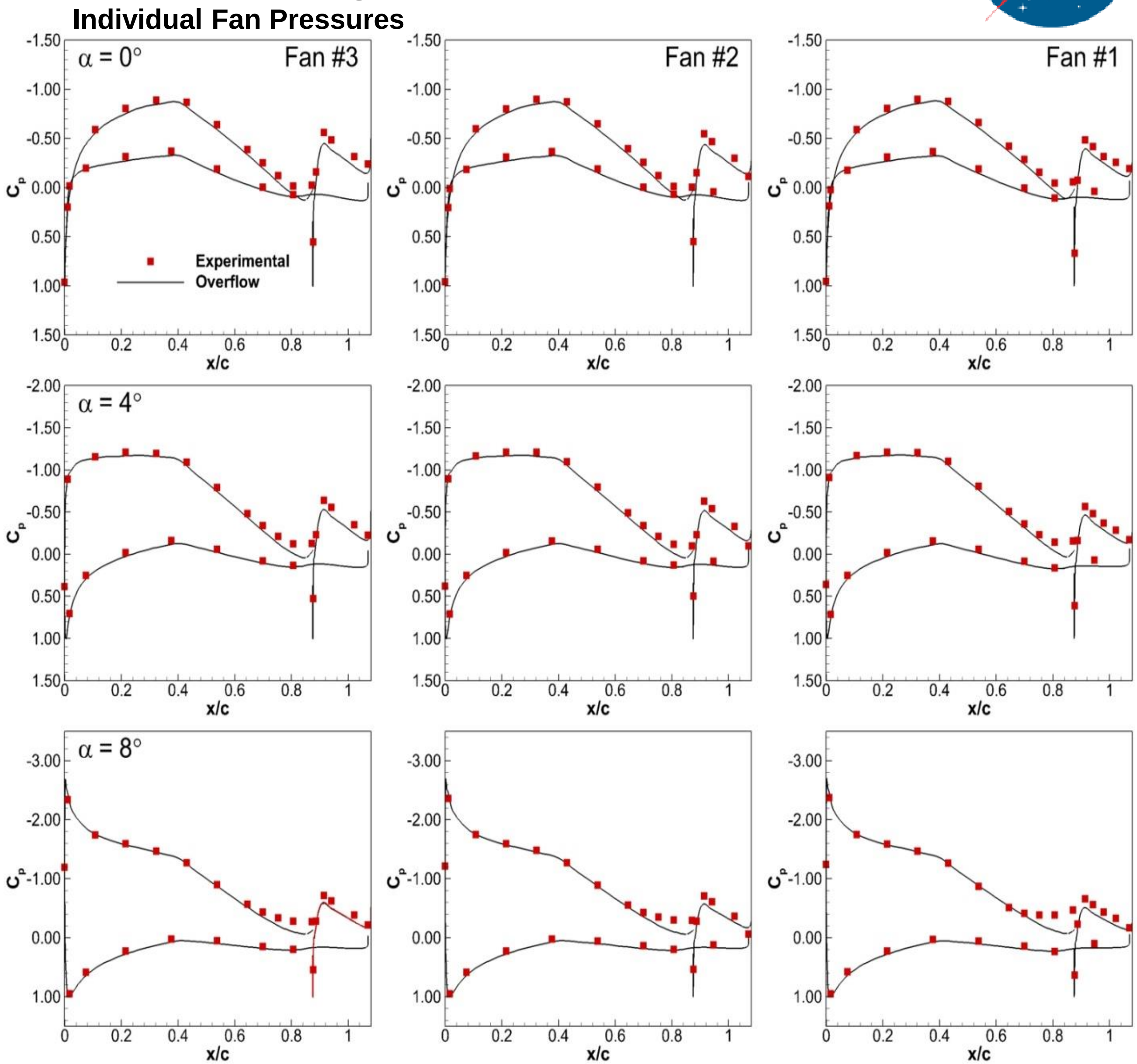
- Overall Exp. Pressures Match CFD Well
- CFD Under Predicts Cowl Pressures
- Small Separated Region Upstream of Inlet For Mid AOAs
  - Inlet Below Design $\dot{m}$
  - Increased Adverse dP/dx
- No Loss in Suction Peak or Upper Surface Pressures With Sep. at High α

Centerline (Fan #3) Pressures



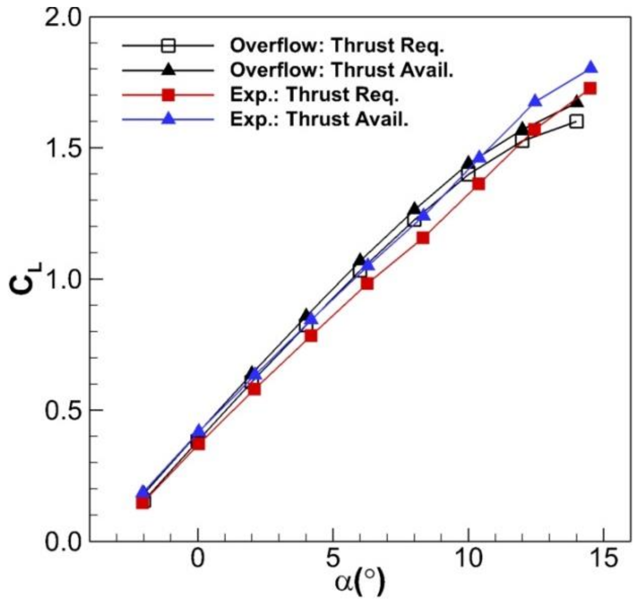
Thrust Required Results

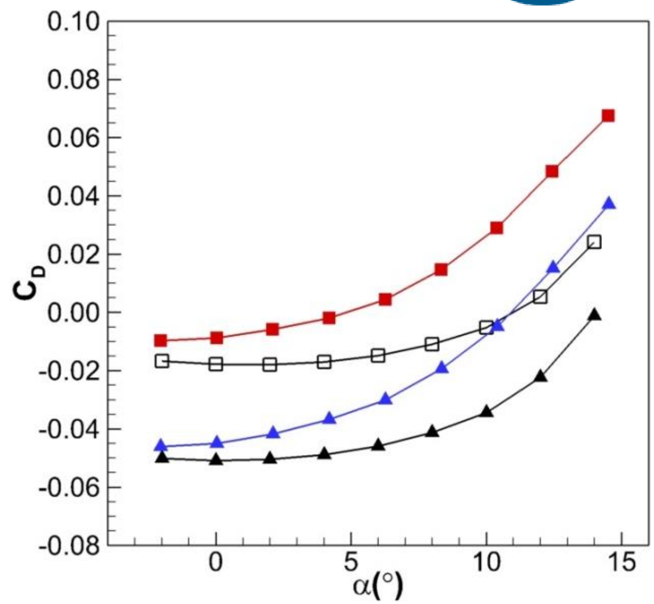
- Again, Overall Exp. Pressures Match CFD Predictions Well
- No Large Fan-to-Fan Differences Observed
- Separated Region Upstream of Inlet Present for All Fans
- Outer Fan (Fan #1) Separated Region Larger
  – Fan #1 Flowfield Affected by Outer Baseline Section, Especially at Higher AOAs

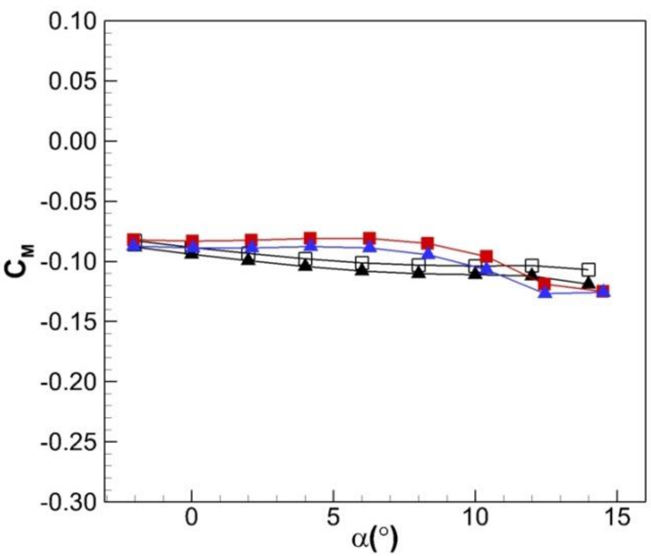


Thrust Available Results

- Better C_L Match Than T_r Case
  - At α = 4°, ΔC_L=0.03
  - At α = 8°, ΔC_L=0.06
  - Better Agreement Tied to Increased Fan Mass Flow
- ΔC_L Between T_a-T_r
  - CFD ΔC_L=0.04
  - Exp. α = 4°, ΔC_L=0.06
  - Exp. α = 8°, ΔC_L=0.09
- T_a C_D Trends Similar as Observed For T_r
- ΔC_M Between T_a-T_r
  - CFD ΔC_M= 7%
  - ΔC_M= 9%



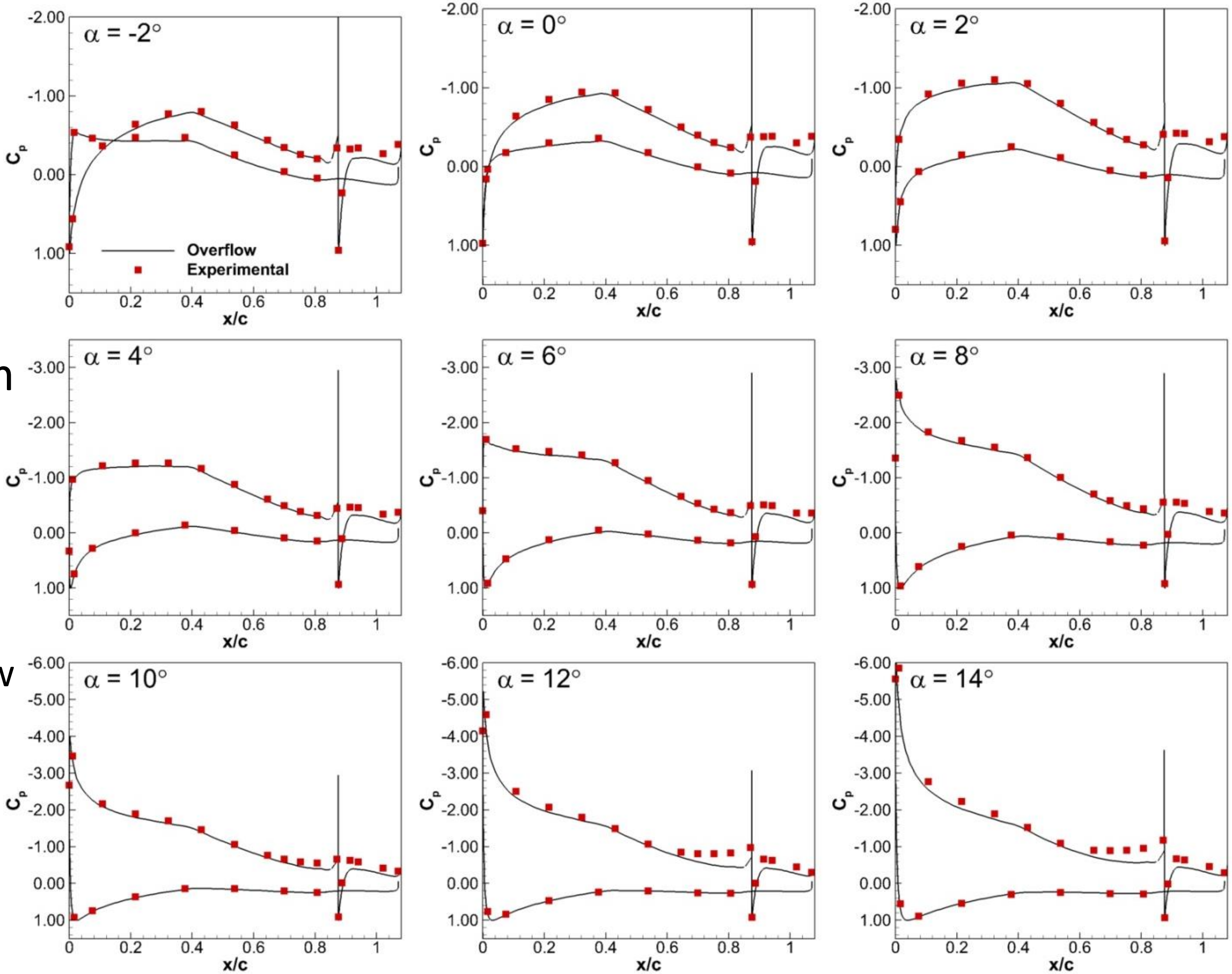




Thrust Available Results

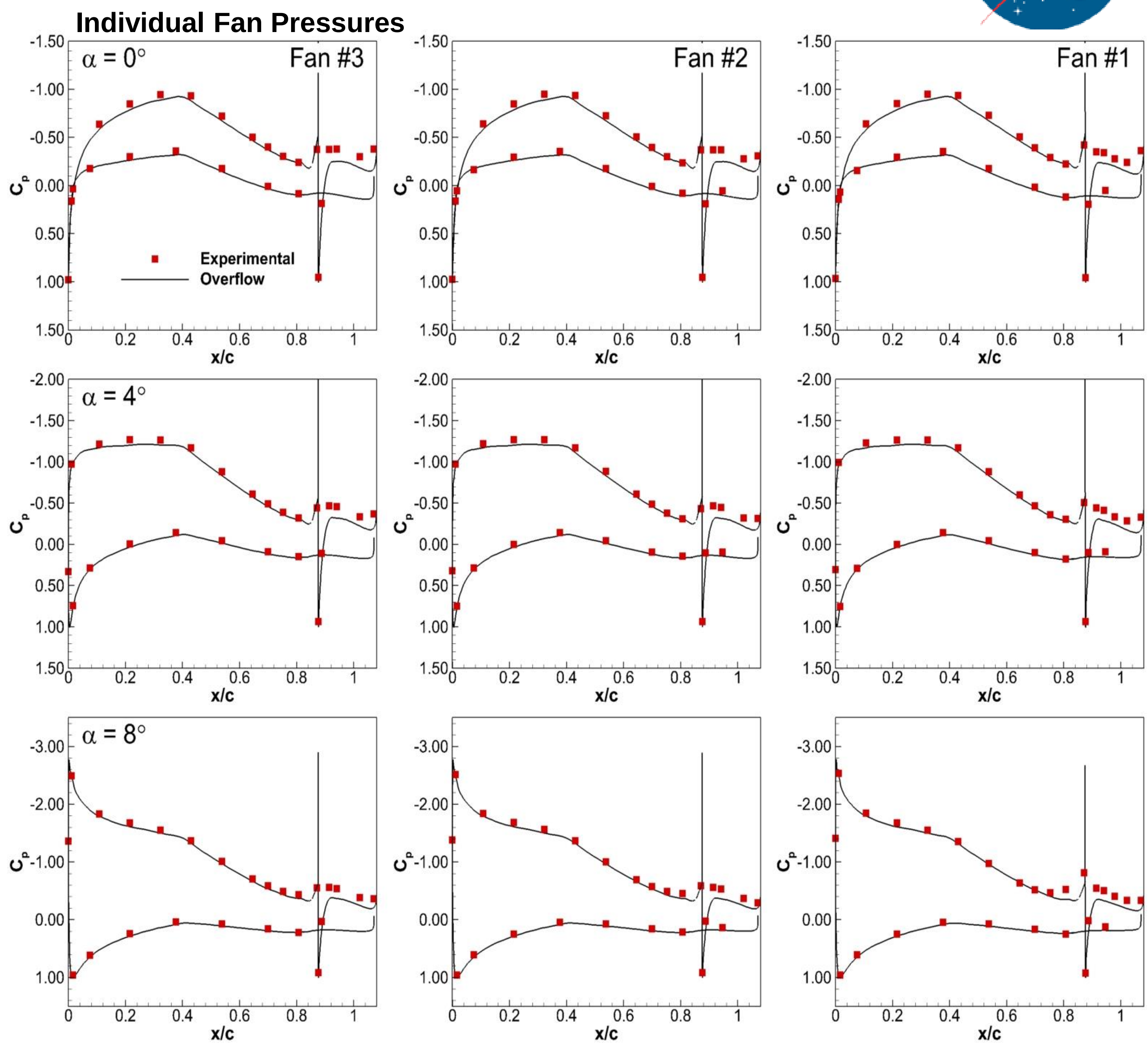
- Exp. Pressures Match CFD Well
- CFD Still Under Predicts Cowl Pressures
- Small Separated Region Upstream of Inlet For Mid AOAs at T_r Absent at T_a
  - Inlet Above Design $\dot{m}$
  - Accelerated Flow Reduces dP/dx
  - Separation Not Visible Until α=12°

Centerline (Fan #3) Pressures



Thrust Available Results

- Exp. Pressures Match CFD Predictions Well
- No Large Fan-to-Fan Differences Observed
  - Increased $T_a\ \dot{m}$ Produces Excellent Fan-to-Fan Flow Symmetry
- Only Outer Fan (Fan #1) Affected by Baseline Section Separation at α=8°



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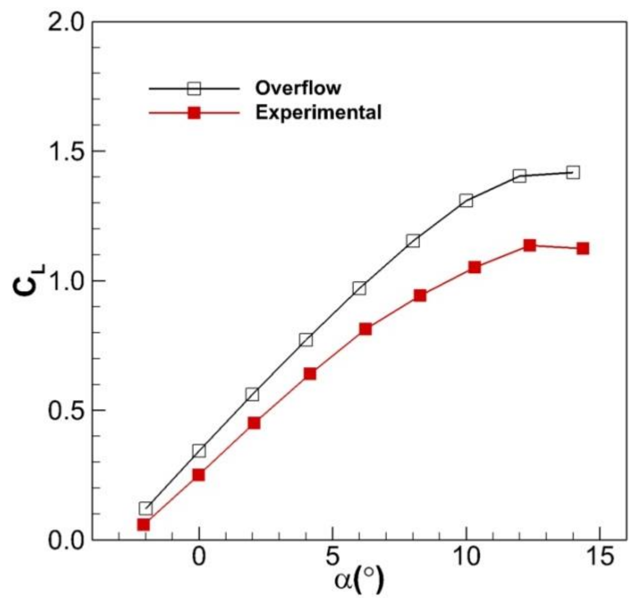
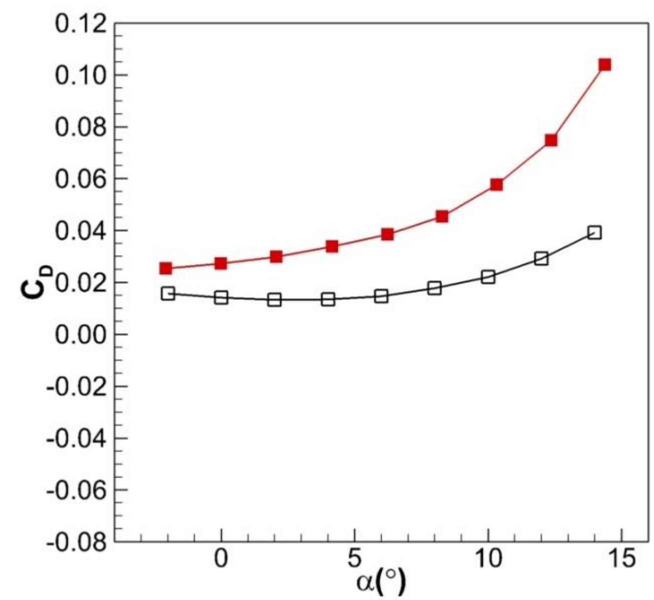
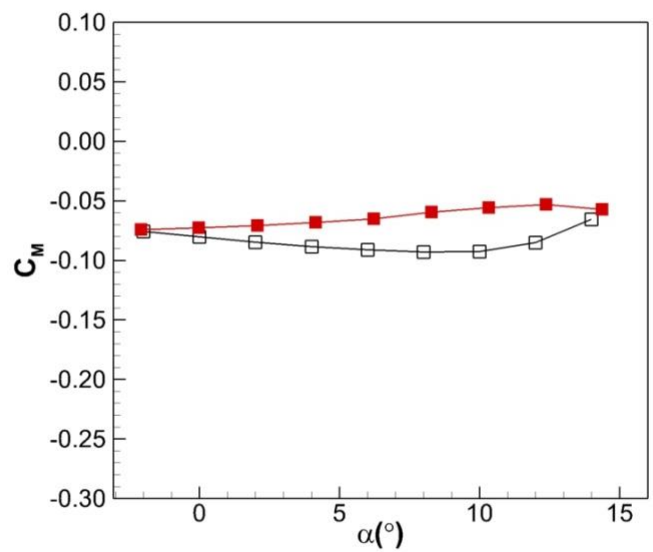
Windmill Results

- CFD Significantly Over Predicts C_L
  - Fan Blades Not Modelled in CFD
  - Exp. Fan Blades Did Not Rotate at Windmill Condition
  - Large Difference in Separation Between CFD and Exp. Case
  - C_D and C_M Show Similar Trends







T_r Diff. Thrust Results

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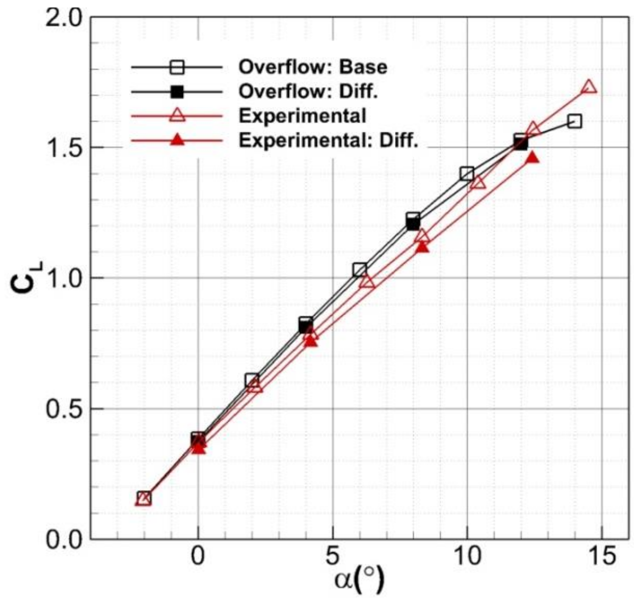
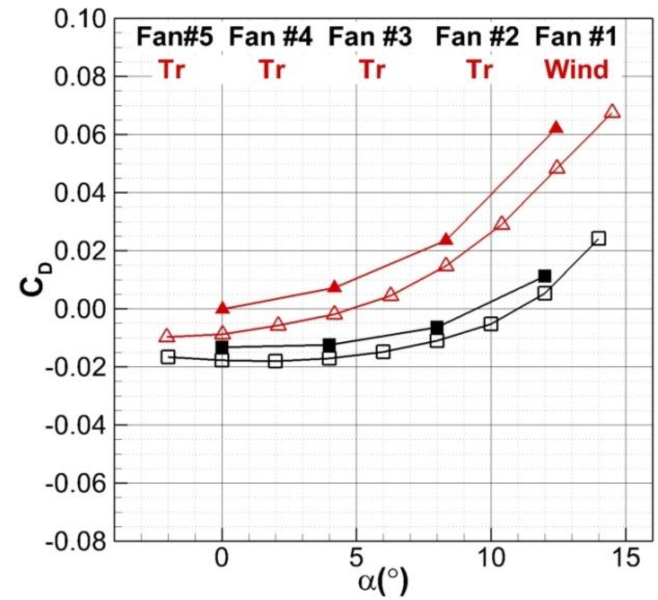
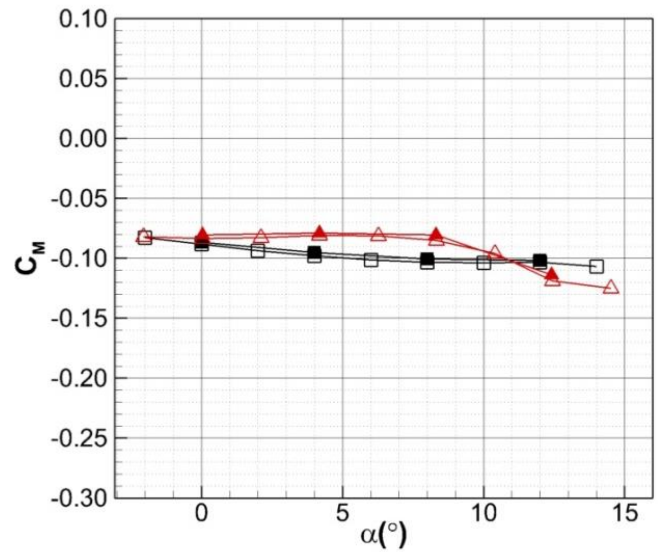
- Differential Thrust Primarily Affects C_D
  - Relatively Constant Offset in C_D With α
- Small Loss in C_L Between Baseline and Differential Thrust Case
  - CFD, ΔC_L=-0.015
  - Exp., ΔC_L=-0.030
  - Increased Exp. Loss Due to Higher Exp. Fan Windmill Blockage
- C_M Unaffected







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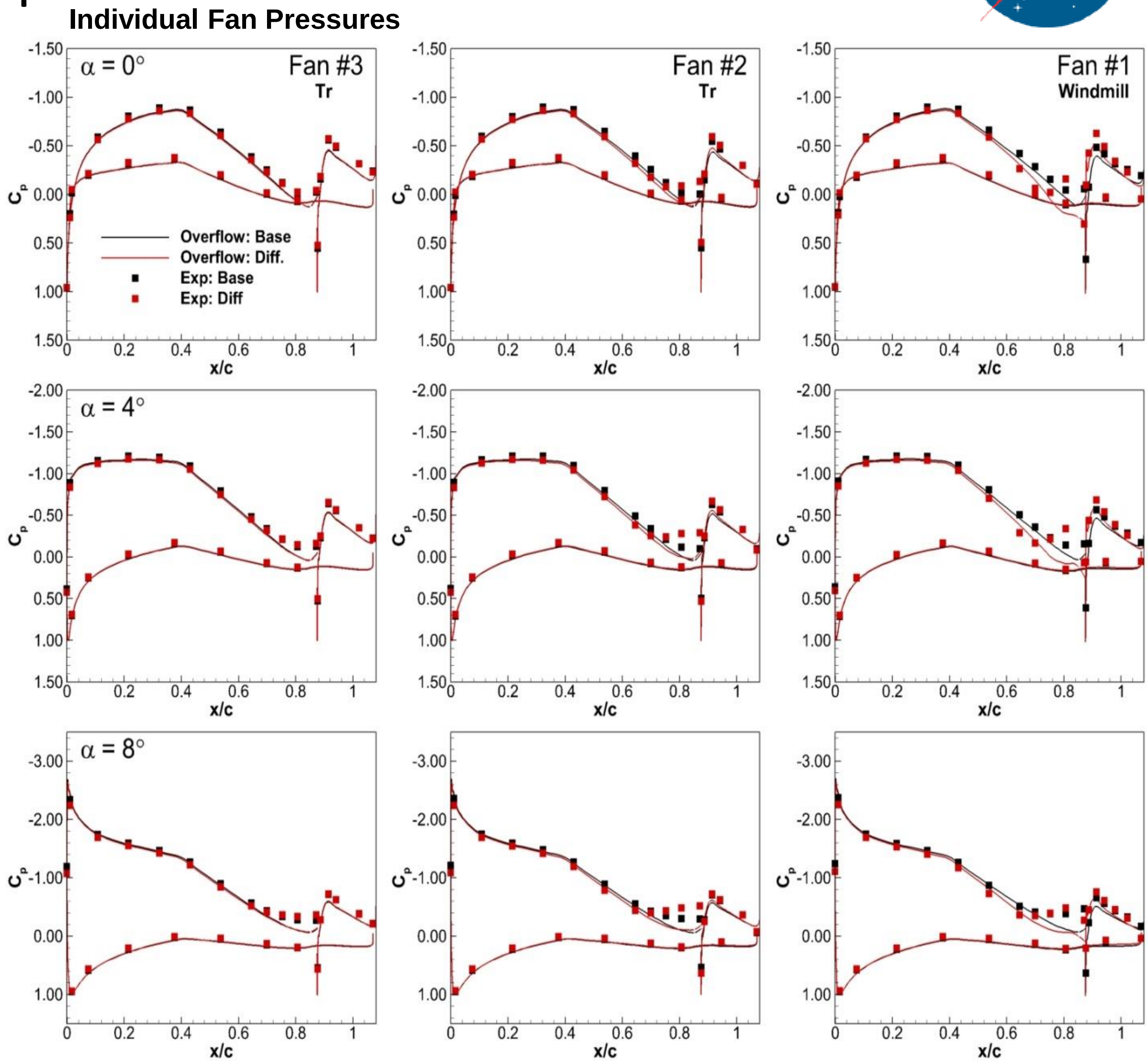
T_r Diff. Thrust Results

- Exp. Pressures Match CFD Well With Exception of Sep. Upstream of Inlet at α=4°, 8°
- Adjacent Fan Impact Limited To Region Just Upstream of Inlet
  - Increased Sep.
- Center Fan (#3) Unaffected By Outer Fan Reduced Mass Flow
- Differential Thrust Effect Confined to Adjacent Fan



T_a Diff. Thrust Results

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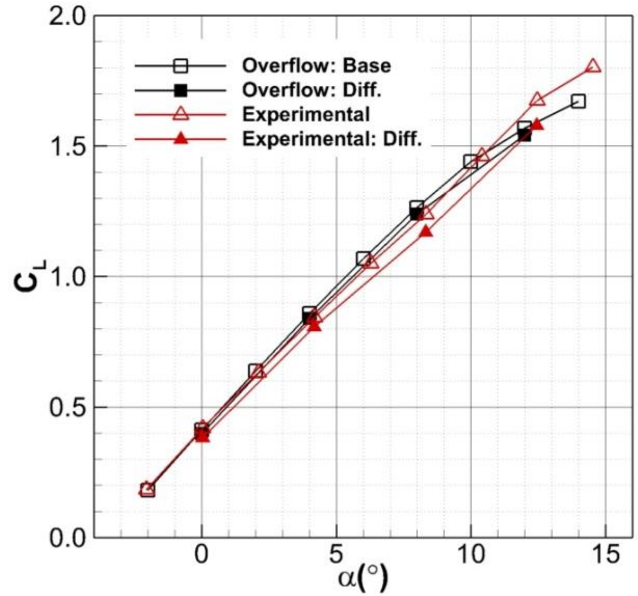
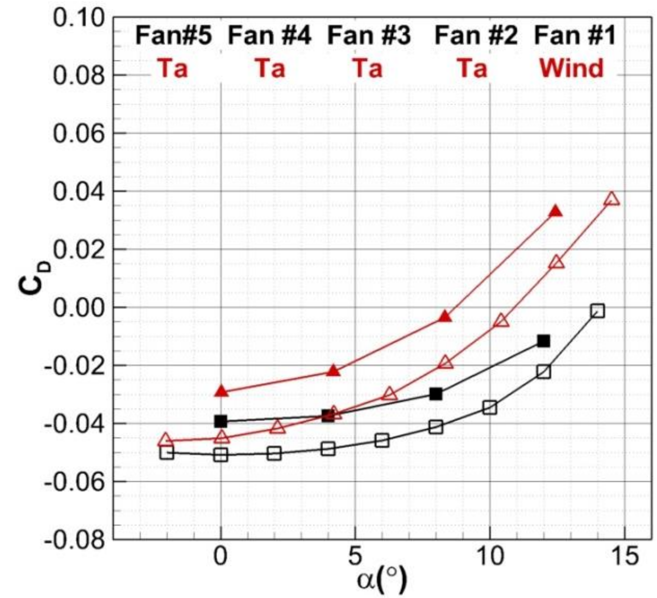
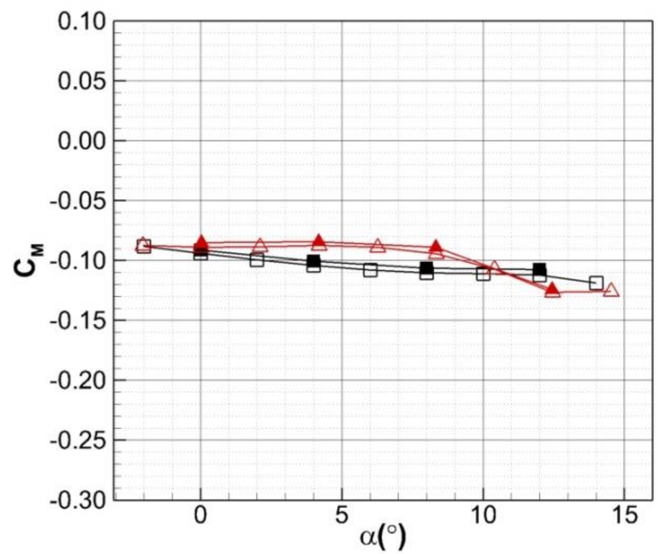
- Thrust Available Results Similar to Thrust Required, With Larger Effect
  - Larger Change in Mass Flow Between T_r-Windmill and T_a-Windmill
- Increased Loss in C_L Between Baseline and Differential Thrust Case
  - CFD, ΔC_L=-0.030 Exp., ΔC_L=-0.050
- C_M Unaffected



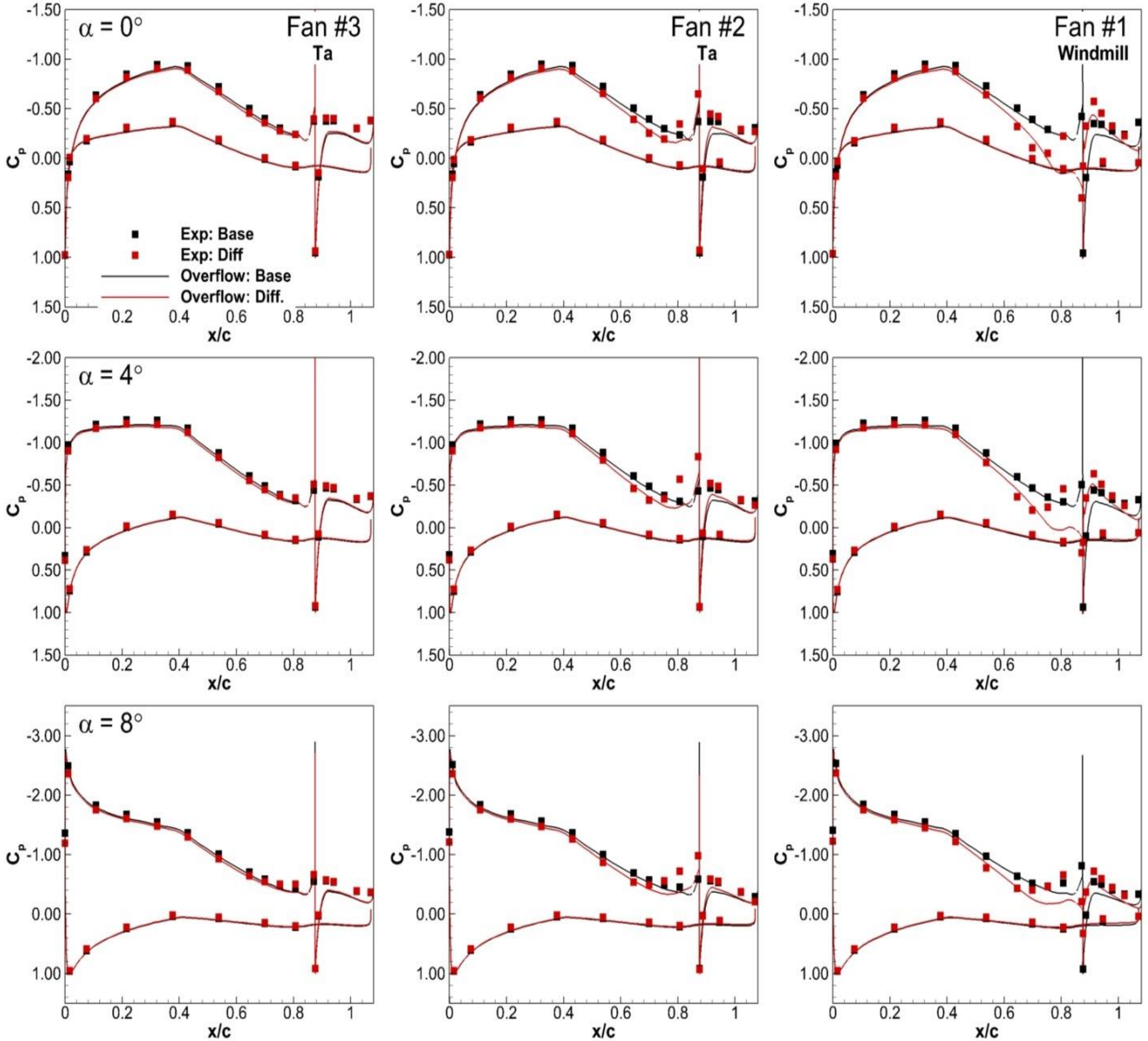




T_a Diff. Thrust Results

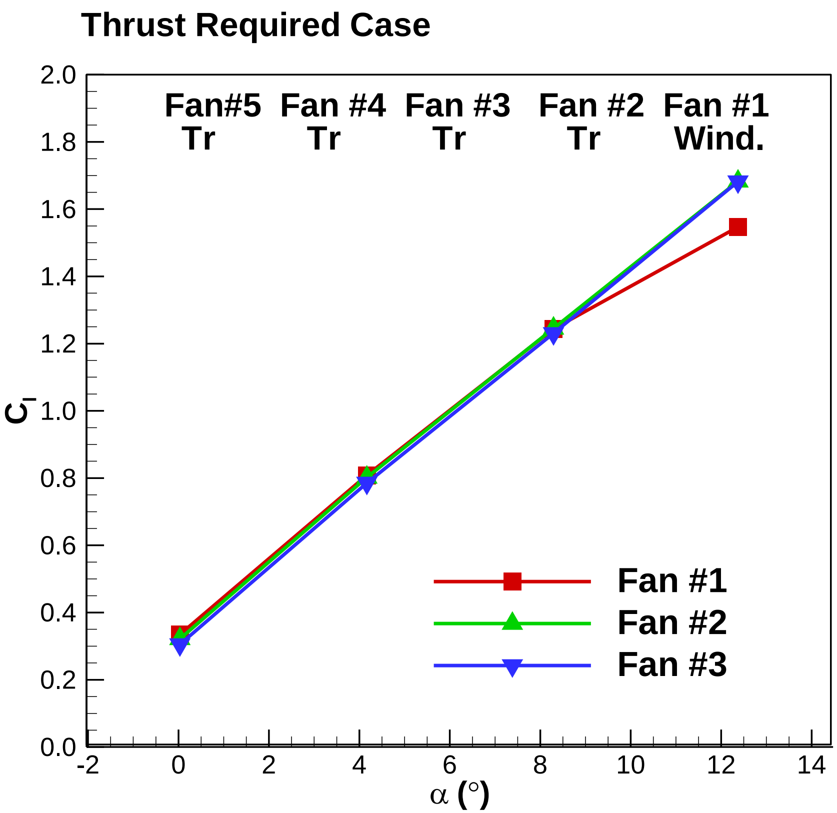
- Even Though $\Delta\dot{m}$ Larger For T_a-Windmill Case, Only Adjacent Fan Pressures Affected
- Impact on Adjacent Fan Limited To Region Just Upstream of Inlet

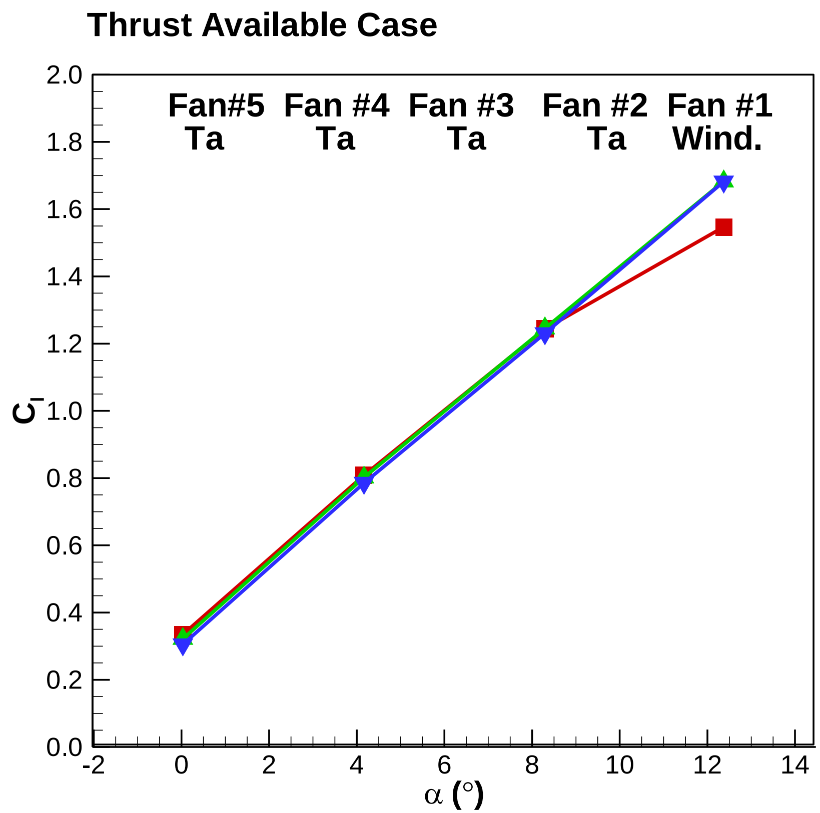
Individual Fan Pressures



Diff. Thrust Results

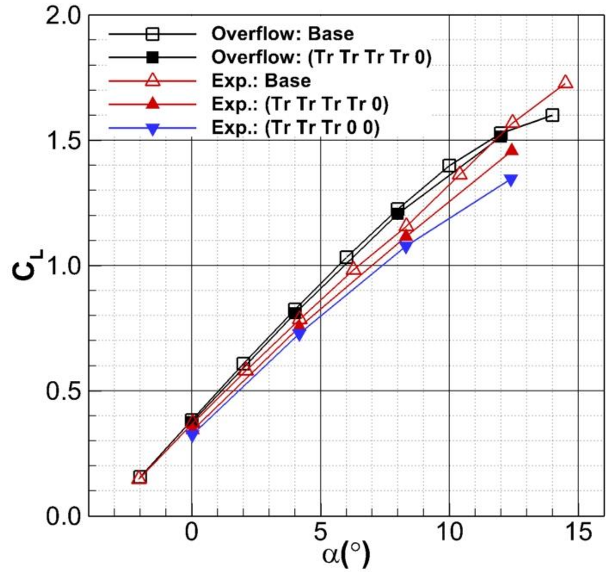
- Integrated Sectional Lift Coefficient
  - Although Small Differences in Surface Pressures Upstream of the Inlet are Observed, Based on Discrete # of Taps Used the Primary Effect of Differential Thrust is Limited To Reduced Mass Flow Fan at High AOA

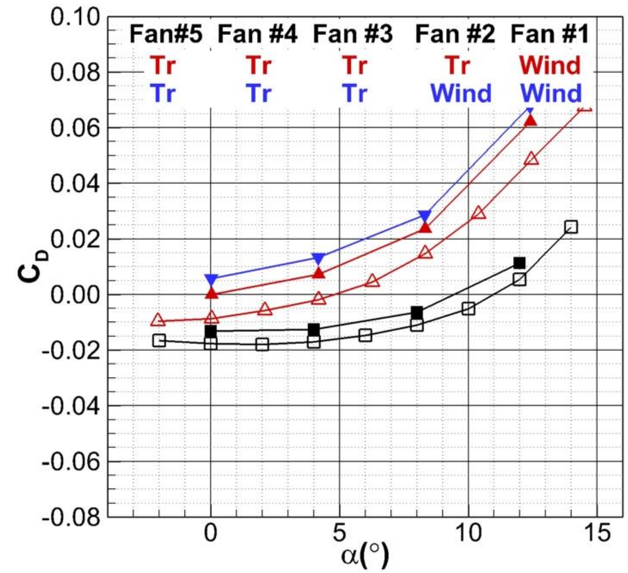


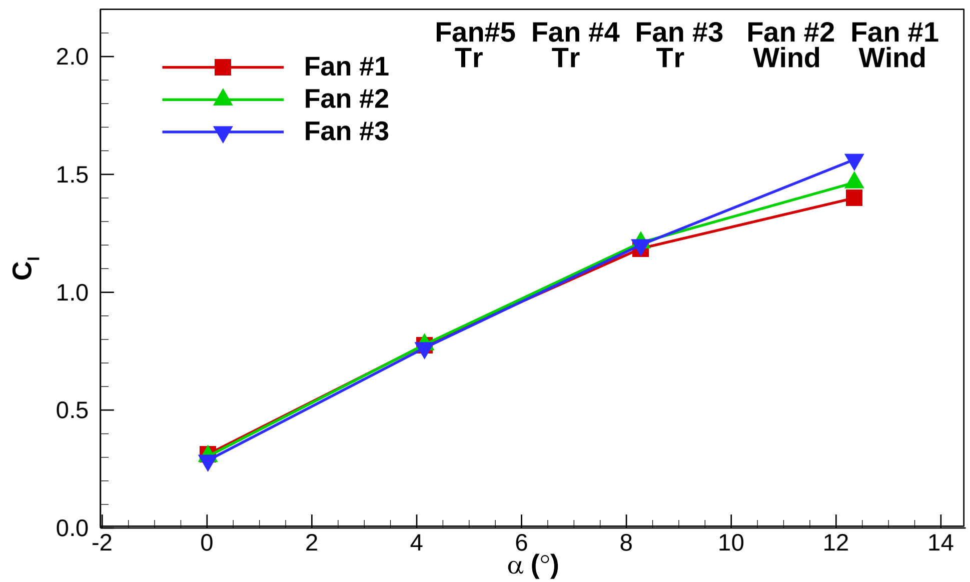


Multi-Fan Diff. Thrust

- Increasing # of Reduced Mass Flow Fans Increases Overall Effect
  - Larger Loss In C_L
  - Larger Increase in C_D
  - Effect Not Linear
- Most Significant Effect at High AOA Where Fan Section Interacts With Baseline Section Separation







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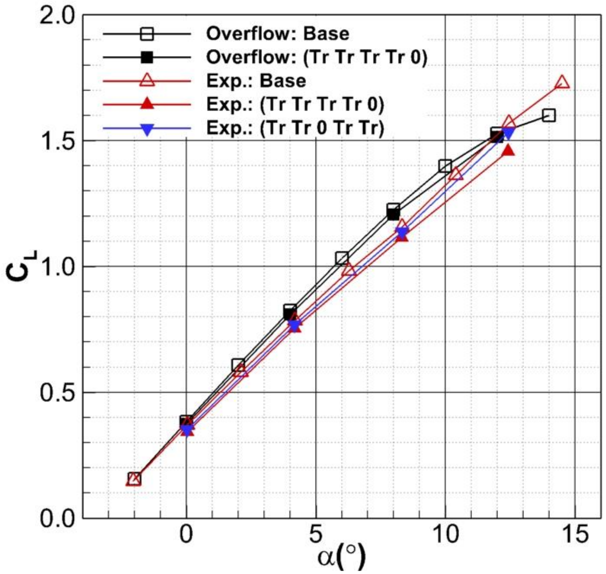
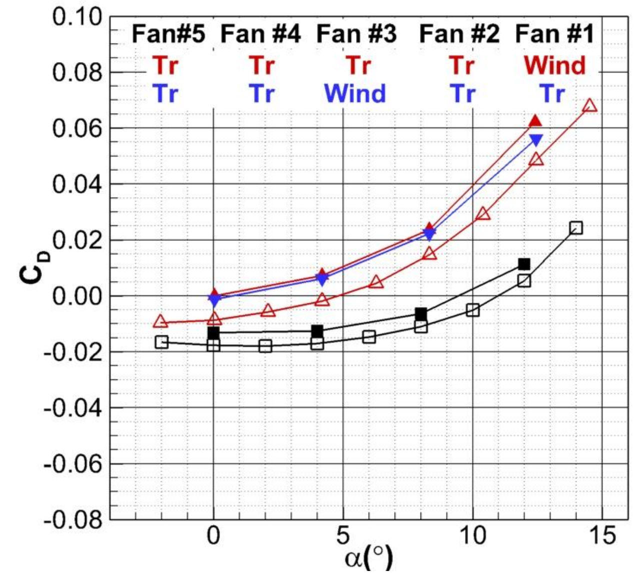
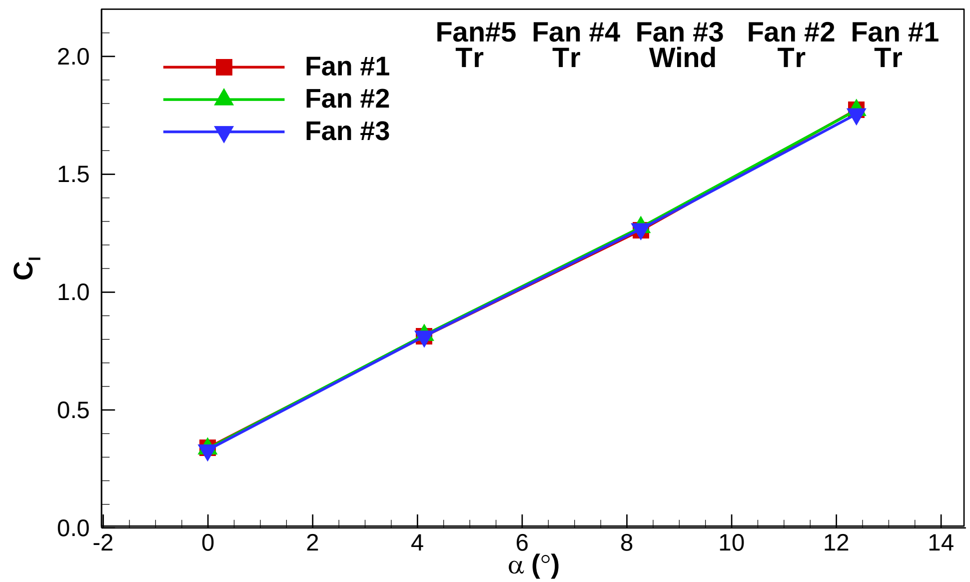
Diff. Thrust Fan Location

- Location of Reduced Mass Flow Fan Important
  - Other Than Increased C_D, Center Fan Windmill Shows Minimal Effect on Overall and Sectional Force and Moment Results
  - Outer Windmill Fans Interact With Baseline Section Flowfield and Separation While Center Fan is Shielded







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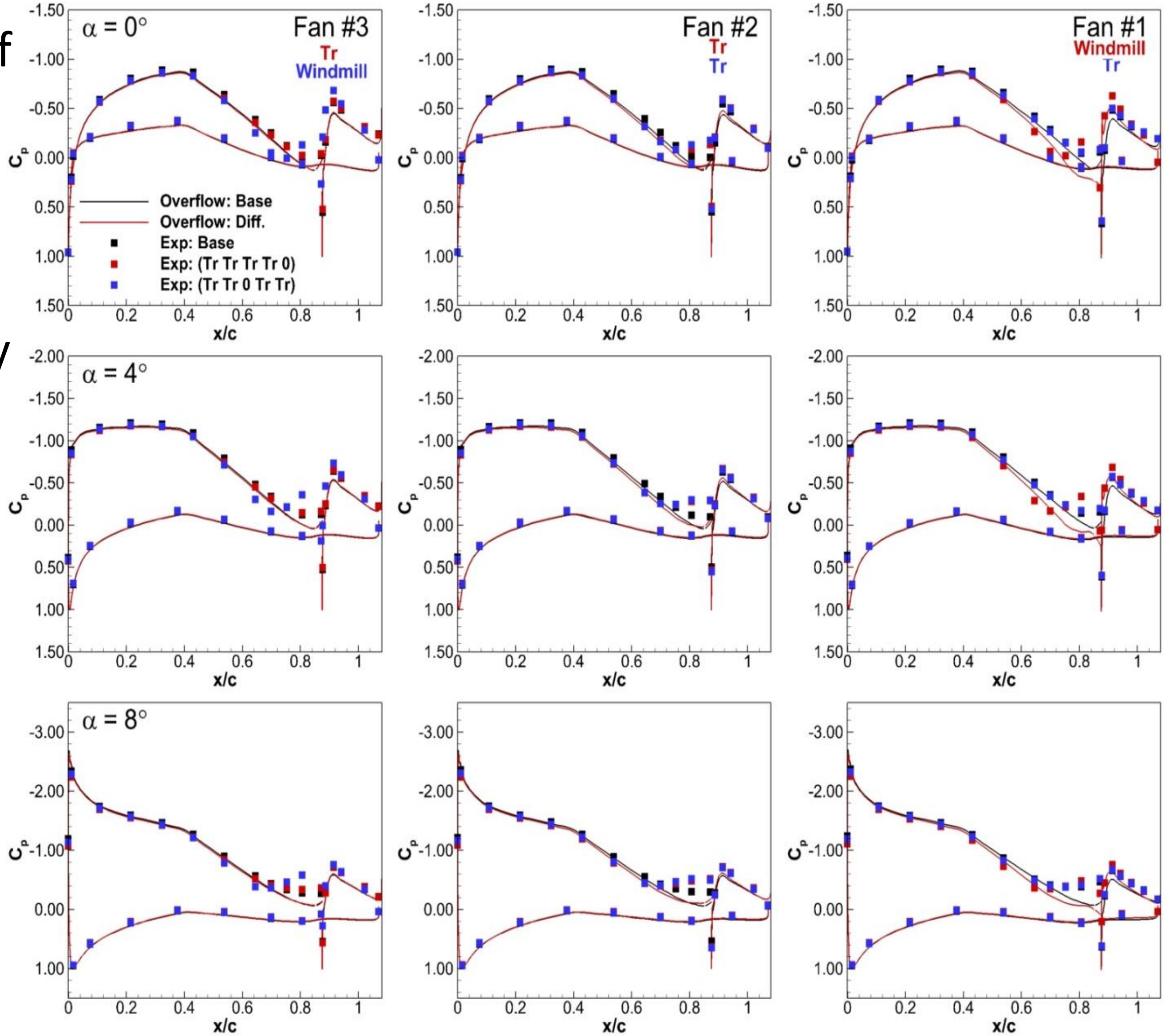
Diff. Thrust Fan Location

- Although Location of Reduced Mass Flow Fan Important For Overall Force and Moment Results, Effect on Adjacent Fan Pressures Nearly Identical

- As With Other Differential Results, Reduced Mass Flow Effect Limited to Adjacent Fan

Individual Fan Pressures



Exp. Conclusions

- Overall Experimental Results Compare Well to CFD Predictions
  - All Major Flowfield Trends and Features Present in CFD Observed In Experimental Results
- Variations in Thrust Level Between T_r and T_a Showed That While Differences in F&M Results Exist, They are Generally Smaller Than Anticipated
  - Increase in C_L With Thrust Level
    - CFD ΔC_L = 3%-4% Between the T_r and T_a Levels
    - Exp. ΔC_L = 5%-6% Between the T_r and T_a Levels
  - Increase in Nose Down C_M With Thrust Level
    - CFD ΔC_M = - 7% Between the T_r and T_a Levels
    - Exp. ΔC_M = - 9% Between the T_r and T_a Levels
  - Variations Smaller Than Previous 2D Predictions
  - 3D Geometry Has Large Relieving Effect
- Exp. Drag Higher Than Predicted For Both T_r and T_a Levels
  - External Motor Wire Routing, Motor Tail Cone, and Sidewall Effects
  - Increased Separation Upstream of Inlet at Moderate AOAs For T_r Case

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Exp. Conclusions

- Both T_r and T_a Levels Showed Increases in Maximum Lift
  - No Loss in Suction Peak Pressures With Separation Upstream of Inlet
    - Attributed to Fan Cowl Upper Surface Remaining Attached Due to Jet Coanda Effect
- Differential Thrust Results Showed Several Interesting Features
- Primary Effect of Differential Thrust on Force and Moment Data is an Increase in C_D with a Slight Reduction in C_L
- Reduced Mass Flow Effects Limited to Adjacent Fan and do Not Propagate Beyond Adjacent Fan
- Increasing Number of Reduced Mass Flow Fans Increases Overall Effect on F&M
- Location of Reduced Mass Flow Fan Important - While Drag is Relatively Unaffected By Location, Lift is Affected:
  - Outer Reduced Mass Flow Fans Interact With Baseline Section Flowfield and Separation, Increasing Overall Effect
  - Inner Reduced Mass Flow Fans are Shielded by Neighboring Fans, Reducing Overall Effect

Program Conclusions

- 5 Fan BLI Pseudo 3D Model Designed, Developed, and Tested
  - Model Based on Flying Test Bed Geometry
- Considering Complexity of CFD and Experimental Models – Results Compare Well
- Thrust Angle Results Showed Most Efficient Design Does Not Replicate Baseline Section Lift Curve
  - Increased Thrust Angle Produces Large Drag and Moment Increase
- Thrust Level Coupling Smaller Than Anticipated
  - Thrust Level Does Influence Circulation
  - Level Smaller Than 2D Predictions
    - Judicious Choice of Thrust Angle Combined With 3D Relieving Effects
- Increased Maximum Lift For TeDP Powered Section
- Differential Results Showed Effect Primarily Limited to Drag
  - Effects do Not Propagate Beyond Adjacent Fan
  - Reduced Mass Flow Fan Location Important
- Although Fixed Inlet Design Can Provide Good Performance, a Moveable Inlet Lip Would Provide Much Larger Range of Separation Free Operation

Next Steps

- TeDP Concept Shows Significant Promise From Both an Aerodynamic and Systems Standpoint
  - Results Show Acceptable Levels of Aero/Propulsive Coupling
  - Differential Thrust Results Show Possibility of Yaw Control
- Program Next Steps Include:
  - Development of Flight Scale Systems
    - Multi-Fan Battery and Battery Management System
    - Multi-Fan Control System
  - Development of Flight Scale Wind Tunnel Test
    - 7’x10’ or 14’x22’ Scale Test
    - Structural Integration of Fan and Inlet/Nacelle Hardware To Test Bed Wing
    - Development and Test of a Movable Inlet Lip
      - Comparison of Added Complexity to Performance Benefits
  - Integration of Flight Scale Systems and Hardware Onto Flying Test Bed Aircraft

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Dissemination

- CFD Design and Analysis Results Presented at 33rd AIAA Applied Aerodynamics Conference:
  - Kerho, M. F., "Aero-Propulsive Coupling of an Embedded, Distributed Propulsion System," AIAA 2015-3162, paper presented at 33rd AIAA Applied Aerodynamics Conference, 22-26 June, 2015, Dallas, TX
- Program Final Briefing at NASA Armstrong Flight Research Center, Sept. 24th, 2015
- Experimental Results to be Presented at 34th AIAA Applied Aerodynamics Conference, June 2016, Washington DC